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Introduction to the Theory of Nuclear Reactions

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1. THE CONSERVATION LAWS

THE study of nuclear reactions is closely parallel to the familiar study of chemical reactions. Many of the ideas familiar in chemistry appear in appropriate form as fundamental notions for the nuclear physicist. The equation of the reaction, the balancing of the equation with respect to the quantities conserved in the reaction, the heat of reaction, the rate of reaction—all of these have their counterparts in the study of the nucleus. The differences in concept are conditioned by the inherent experimental differences between the two fields. The energy of chemical reaction is the energy of electron bonds, whereas that of nuclear reactions involves the binding of nuclear particles. The energy of a molecular reaction is of the order of a million times smaller than the energy of a typical elementary nuclear process. The chemist uses moles of the reactants; but the nuclear physicist can measure the properties of a few thousand particles, or even of a single particle, this being possible because of the relatively large energies involved. Thus we shall work with quantities defined per particle and consider the individual collisions rather than use gram molecular weights and the laws of mass action.

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We shall examine a nuclear reaction as an individual process, and apply our results to the study of experiments that involve large numbers, though for the most part entirely microscopic masses, of the nuclei concerned. Each nucleus taking part is designated by its symbol as an element, to which is affixed the mass number A and often prefixed the atomic number Z. The *mass number* A is defined as the number of heavy particles (protons and neutrons) in the nucleus, and is the integer nearest the atomic weight of the isotope. The *atomic number* Z is the charge of the nucleus expressed in terms of the electronic charge taken as the unit; in other words, Z is the number of protons contained in the nucleus, and is also the number of electrons in the complete neutral atom. Since Z is determined by the chemical symbol, to specify it separately is unnecessary, though often convenient. Certain particles, such as the neutron, electron and positron, are given special symbols. In this notation, a sample reaction is

$$_{11}\mathrm{Na}^{23}+{}_{1}\mathrm{H}^{1}\rightarrow{}_{12}\mathrm{Mg}^{23}+{}_{0}n^{1},$$

where ${}_{0}n^{1}$ denotes the neutron.

In the great bulk of nuclear reactions a massive "target" nucleus is bombarded by a relatively light nucleus, and the product emitted is another light nucleus, with the target nucleus changing into a nuclear species differing by only a few units in A and Z. This has given rise to another scheme of notation in which one writes first the target, then a bracket containing symbols for the bombarding and emitted particles in order, and finally the residual nucleus. The foregoing reaction would be written ${}_{11}\mathrm{Na}^{23}(p, n){}_{12}\mathrm{Mg}^{23}$.

What are the rules for balancing such equations? Or, physically speaking, what properties of the system remain unchanged during the reaction? These are already implied by the way we have chosen to write the reaction. The electric charge is conserved; the sum of all Z's must be the same in both members of the equation, counting electron and positron as -1 and $+1$ units, respectively. A proton can change into a neutron, but a positron must appear or an electron disappear in the process. Sometimes an electron is created without changing the charge of any heavy particle; then a positron must appear also, and the total charge of the pair is zero. No exception to this conservation of charge has yet been found, and the creation and disappearance of electron-positron pairs is a dramatic confirmation of the validity of this principle.[1]

Unlike positrons and electrons, neutrons or protons do not appear and disappear, though one may change into the other. The total number of heavy particles—that is, the total value of A—is the same on both sides of the equation. The creation or destruction of such a heavy particle as the proton or neutron would involve an energy transfer of some 10^9 ev. Even in cosmic rays, where such energies are available, no such process has yet been recognized.

So far we have pointed out some properties peculiar to nuclear matter that are conserved during a reaction. There are also general mechanical quantities that are conserved in a nuclear collision, at least to an order of accuracy beyond experimental interest. These quantities are total energy, momentum and angular momentum. We would, of course, expect constancy of total energy, since there is no external source of energy for the colliding particles. The energy of chemical binding that holds the nucleus in the solid material of the target is only a few electron volts per particle, usually negligible in comparison with experimental error. It is necessary to include in the total energy the kinetic energy, the potential energy of repulsion of the colliding charged nuclei (negligible at macroscopic distances) and the energy equivalent of the mass of the reactants.

The equivalence of mass M and energy E, expressed by the relation $E=Mc^2$, where c is the speed of light, is a simple consequence of the ideas of restricted relativity.[2] Its best experimental verification is found in the energy balance of nuclear reactions. In chemistry it is sufficient, though inexact, to say that mass is conserved, because the energies released are such a small fraction of the total mass-energy. The mass of two hydrogen atoms and one oxygen atom in the free state is, in fact, larger than the mass of a water molecule, but only by 1 part in 10^9. The equivalent mass of the energy of reaction per molecule and the mass of the water molecule are exactly equal to the total mass of the three free atoms. It is the same with nuclei, but the mass changes coming from the binding energies of nuclear particles are measurable fractions of the total mass, and must be taken into account.

[1] W. Heitler, *Quantum theory of radiation*, p. 187.
[2] See, for example, A. Einstein, Bull. Am. Math. Soc. 41, 223 (1935).

The total momentum of the colliding particles, measured in any reference system, is also unchanged during collision, since the forces in any direction acting on the system are negligible. This is immediately proved by the fact that the cloud-chamber tracks of reactants and products lie in a plane.[3]

Since no forces act on the colliding particles, no torques act about any axis; the total angular momentum of the system, as well as its component in any given direction, must be constant. The angular momentum of the system consists of the intrinsic angular momentum of the reacting particles combined with the orbital angular momentum of their relative motion. It is this sum (combined according to the rules of quantum mechanics) that must be conserved, though differing amounts of the total may be assigned to the relative motion of the product nuclei. Experimental verification of the conservation of angular momentum is not easy, since we cannot directly measure the angular momentum of a single particle. But statistical predictions concerning the angular distribution of reaction products made by quantum-mechanical methods on the basis of this conservation are satisfactorily verified, and the idea of such conservation is fundamental in the theory.[4]

By measuring the energies of projectile and emitted particle, and applying the conservation laws for energy and momentum, the energy released in a reaction can be calculated. If the energy thus released is called the Q of the reaction, we have (for the reaction $T(i, p)R$),

$$Q=c^2(M_T+M_i-M_p-M_R)$$

and

$$Q=E_i\left(1-\frac{M_i}{M_R}\right)-E_p\left(1+\frac{M_p}{M_R}\right)+2\frac{(M_pE_pM_iE_i)^{\frac{1}{2}}}{M_R}\cos\theta_p,$$

where the kinetic energy and mass of particle i are denoted by E_i and M_i, etc., and the angle between the incident beam and product p is denoted by θ_p. The measurement of reaction energies is an important experimental field, involving special technics. An important method for measuring the energy of fast particles is to use the relation between the energy of such a particle and the distance it will travel in air or some denser absorbing medium, called its *range*.[5]

[3] First quantitatively checked by P. M. S. Blackett, Proc. Roy. Soc. **A103**, 62 (1923). For further checks, see *B4*, Table LXXII. The letter *B* denotes an item listed in the Bibliography at the end of this paper.

[4] Compare *B6*, p. 47.

[5] Range-energy relations have been discussed in detail both from an experimental and a theoretical point of view. See *B4*, secs. 95–96. For later data and analytic approximations to curves, see Rogers and Rogers, Phys. Rev. **53**, 713 (1938).

[6] Mott and Massey, *Theory of atomic collisions*, pp. 20 ff.

2. The Data of Nuclear Reactions

The conservation laws are satisfied in each single nuclear collision. But we are also concerned with knowing *how many* nuclear processes take place under the given conditions of an experiment. It is impossible to tell whether, say, the next proton incident on a lithium fluoride target will initiate a transmutation; but both experiment and theory give us the likelihood, the *probability*, of the process. Then we can predict accurately that a certain fraction of a beam of incident protons will enter the lithium nuclei of the target.

The simplest expression for the probability of a reaction is the *yield*, or number of individual processes that occur for a given number of incident particles. The statement that the reaction $Li^7(p, \alpha)\alpha$ has a yield of 1/2000 at 3 Mev means that one Li^7 nucleus divides into α-particles for every 2000 3-Mev protons stopped in the material of the target. This specification is incomplete, since it depends on the experimental arrangement. For absolute measurements of yield, one must know how many target nuclei were presented to the beam; thus the absolute yield will vary with the density of the target, the distance the beam penetrates and the way in which the probability of reaction varies with the energy of the projectile. For, as the particles of the beam penetrate the target, they lose energy until, if the target is sufficiently thick, they finally stop. For accurate measurement, a thin target layer should be employed. "Thick-target" yields represent some sort of integration over the energy range of the slowed-down beam particles, and require special treatment for accurate interpretation. When the target is very thin, and the particles of the beam consequently lose so little energy in traversing it that the probability of the reaction is essentially unchanged, we have "thin-target" yields. Thin-target yields refer to a given energy of incidence.

A complete specification of the probability of a reaction is given by the *cross section*.[6] A cross section σ_{AB}, for a reaction in which the incident particle is called A and the emitted particle B,

is defined by the equation $n_B = I_A \sigma_{AB} N$. Here N is the number of target particles presented to the beam (for example, for thin targets N is the product of beam area, target thickness and target density), n_B is the number of particles emitted per unit time, and I_A is the number of particles A incident per unit area and time. The cross section for any process is equal to the area of the incident beam from which particles are removed by the given process, when the beam is directed at a single target particle. If no wave effects came in, the total cross section would be just the geometrical area of the target.

We can specify a cross section for any process; for example, we can assign a cross section for the emission of γ-rays of energy E in the direction specified by the polar angles (θ, ϕ) when protons are captured by lithium. Then the number of rays emitted in that direction with energy E per unit solid angle and per unit energy for $I_p = 1$ is just $\sigma_{p\gamma}(E, \theta, \phi) dE d\phi d(\cos\theta)$ for every lithium nucleus of the target. Here $\sigma_{p\gamma}$ is called a *differential cross section*, since it is given for an infinitesimal range in energy about E and in direction about (θ, ϕ). The total number of γ-rays of any energy in all directions is found by integrating over all directions and energies. Then the number of γ-quanta is

$$\Sigma_{p\gamma} = \int_0^\infty dE \int_0^{2\pi} d\phi \int_1^{-1} d(\cos\theta) \sigma_{p\gamma}(E, \theta, \phi),$$

where $\Sigma_{p\gamma}$ is called the *total cross section for proton capture by lithium*. In this way any process or partial process can be described by giving the appropriate cross section.

The probability of a nuclear process depends, of course, on what process it is—that is, on the particular particles involved in the reaction. It also depends on the variables of the collision. As it happens, the quantities most easily controlled experimentally also give much information about the reaction. These include the energy of the incident particle, which depends only on the speed of the particle and the angle between the incident direction and the direction of emission of the product. The study of the cross section as a function of the angle of emission—that is, the angular distribution of the product—leads eventually to information about the angular momentum properties of the reaction. The study of the cross section as a function of energy is the main problem of the theory. The probability of the reaction, expressed as a function of the bombarding energy, either absolutely as a cross section or only relatively as a yield, is called an *excitation function* for the reaction.

FIG. 1. Excitation curves for the reactions produced by protons incident on Li^7. The single, sharp resonance level in the γ-ray yield and the smooth rise of the α-particle curve are typical for the lightest nuclei. The qualitative difference between these two reactions coming from identical reactants shows the extreme importance of selection rules in the region of light nuclei. (All figures in the present paper are based on experimental results, but are simplified for purposes of illustration.)

(It is sometimes called a *transmutation function* when the reaction concerned involves a change of chemical identity.) The chief data of nuclear experiments are the angular distributions and the transmutation functions, which can be reduced to a knowledge of the cross section as a function of energy and direction.

3. Problems for the Theory

What are the phenomena of nuclear reactions that we must try to understand?[7] There are a variety of projectiles: neutrons, protons, deuterons, α-particles, even γ-quanta. They may have energies ranging from that of the slow neutron, 1/30 ev, to that of the fastest α-particles, 30 Mev. The products of nuclear reaction depend on the reactants—projectile and target—and on the energy of incidence. The time required for nuclear processes may be ten times that required for a fast proton to cross the lithium nucleus, about 10^{-22} sec, or as long as the lifetime of the yttrium formed by bombardment of strontium with fast deuterons, hundreds of days. For nuclear processes such as the disintegration of uranium by emission of an α-particle, or the typical β-decay, say, of an isotope such as P^{32}, a billion years or only a few days may be required. The cross sections of nuclear

[7] For typical data: *Li reactions*, Rumbaugh, Roberts and Hafstad, Phys. Rev. **54**, 657 (1938); *slow neutrons*, *B2*, secs. 60, 61; *fast neutrons*, Grahame and Seaborg, Phys. Rev. **53**, 795 (1938); *competition*, H. Newson, Phys. Rev. **51**, 620 (1937).

reactions, whose course a complete theory must some day predict, may vary no less widely. The cross section for the disintegration of Be^9 by γ-rays of energy 3 Mev, is about 10^{-27} cm², or 1/1000 of the geometrical area of the copper nucleus. The cross section for the capture of slow neutrons by gadolinium is 3×10^4 times the actual nuclear area of Gd. In this slow neutron work we see the complete inability of simple classical mechanics to explain nuclear phenomena, and the necessity for new concepts, the concepts of quantum mechanics. For how can a nucleus that exerts no force outside of a region a few times 10^{-13} cm in diameter act to absorb neutrons over a distance 150 times as great?

The dependence of cross section on energy may be a smooth exponential rise from zero, as with the reaction $Li^7(p, \alpha)\alpha$, around a few hundred kilovolts (Fig. 1). Or, *with the same reactants*, there is a negligible yield of γ-rays, except for one enormous peak at 440 kev. It may show many sharp peaks, a few hundred volts wide and a thousand times as high as the troughs between them, spaced every few dozen kilovolts, as in the reaction $F^{19}(p, \gamma)Ne^{20}$ (Fig. 2). Or, as in the slow neutron reactions, it may show peaks still closer, spaced perhaps 100 v apart, and rise without apparent limit as the neutron energy grows less and less. The cross section for the reaction $Pb(n, n)Pb$, on the other hand, does not vary by more than a few percent from the geometrical cross section over a range of millions of electron volts in bombarding energy, once the energy is above a few million electron volts (Fig. 3).

And what of the direction of reactions? When N^{14} is bombarded by α-particles, the only reaction observed at first is $N^{14}(\alpha, p)O^{17}$. When the beam energy passes 5 Mev, one begins to observe neutrons, and fewer protons are produced. This phase continues as the energy increases until, at 8 Mev, only neutrons and a few protons are observed. But the total cross section for both these processes taken together is slowly and smoothly rising. (See Fig. 4.)

These, then, are the problems set for our theory. It must explain the resonance effects, such as those for the fluorine and lithium γ-rays and for slow neutrons; it must give an account of the rapid but smooth variation for reactions such as $Li^7(p, \alpha)\alpha$, and of the constant cross section for $Pb(n, n)Pb$. It must explain the competing products from N^{14}. It must make reasonable the large cross sections and the small; it must show how the times involved can vary by a factor of 10^{35}. We do not yet have a theory that yields this complete picture; indeed, some of the most fundamental phenomena are not well understood. But we do have a theory whose broad outline and many of whose detailed predictions are confirmed by innumerable experiments in a way from which there is no retreat. It is very satisfying when an experiment confirms each new calculation from this still imperfect theory; and there are many predictions which we are confident no experiment will ever deny. An account of this still-growing and changing theory, especially its main ideas and more general statements, will be given here. The experiments are complex; the theory must still be modest before them. But its root ideas are firmly fixed in our knowledge of modern physics.

4. Quantum Preliminaries

The study of the nucleus is based on quantum mechanics, which has had thorough experimental verification in the atomic domain. While wholly new concepts will probably be required for eventual complete understanding of nuclear phenomena, the general results of quantum mechanics, learned from the atom, are still applicable to the even smaller distances and shorter times of the nuclear domain. Quantum-mechanical description emphasizes the dual aspect of phenomena, according to which we speak of the wave or of the particle picture, depending on the experimental arrangement and the physical circumstances. Thus, we may give to electromagnetic waves a quantum, or photon character; for light of circular frequency ω, there are quanta of energy, $E=\hbar\omega$, where $2\pi\hbar=h=6.55\times10^{-27}$ erg sec. We may describe a stream of free particles of mass m and speed v in terms of a plane wave of wave-length $\lambda=\hbar/mv$; the square of the absolute value of this wave function is equal to the probability of finding a particle in unit volume at the point specified.[8] For particles that are under the influence of forces, and for

[8] *B5*, p. 57 (9); *B1*, pp. 9–10.

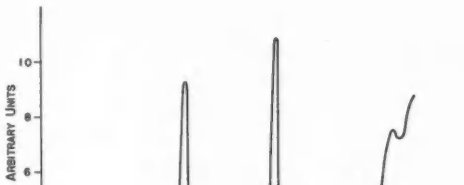

FIG. 2. The great complexity of the fluorine γ-rays and the enormous amount of well-defined structure show how rapidly the number of energy levels increases as we go to heavier nuclei. Contrast with the single lithium resonance.

systems of many particles, a more complicated wave function can be written; it will depend on all the degrees of freedom of the system, and its absolute square will be the probability of finding the system in the configuration specified. In every case the wave-length is a measure of the distance within which the particle can be localized. (Strictly speaking, a single wave-length refers to *free* motion, say, of the center of mass of a system; an individual particle or system that is moving under the influence of external forces must be described by a whole packet of waves of various wave-lengths.) The suitability of the wave description or of the particle description in a particular case is determined by comparing the wave-length with the physically important dimensions of the problem. If the forces on the particle do not change appreciably within the distance of a wave-length, the particle will follow the trajectory prescribed by ordinary mechanics, and we can speak of the path of an individual particle without sizable error. If, on the other hand, the forces vary rapidly within the distance of a wave-length, we cannot then speak of classical orbits at all, but must base our description on the notions of the wave function, which will "diffract" in the field of force.

There is a close analogy in this situation to the distinction between geometrical and physical optics. As long as we deal with lenses and mirrors, where the dimensions over which the refractive index changes are large compared with the wave-length of light, we can use geometrical optics, and trace ray paths with good results. But when we deal with tiny slits or dust particles, where the refractive index changes appreciably within a wave-length, we must consider the wave nature of light and the effects of interference and diffraction.

We encounter both domains in nuclear physics. The wave-length of a particle depends on its mass and velocity. The wave-length of a slow neutron of energy 1 ev is 10^{-11} cm, about 100 times the nuclear diameter. Collisions of such particles must be described in terms of the wave picture. This is the key to the enormous cross section of slow neutron reactions. We are there dealing, not with a well-localized particle which can either strike or miss the nuclear target, but with a wave, which is diffracted and absorbed by the nuclear matter. The scale of the effect will be the wave-length and not the dimensions of the nucleus. But for fast, 10-Mev neutrons, the wave-length is only a fraction of the nuclear diameter, and we can speak with accuracy of the paths during a collision.

The uncertainty principle, the fundamental relation of the quantum mechanics, will yield simple results for our discussion. The familiar form of this relation is the inequality $\Delta x \Delta p \geqslant h$. Here Δp is a measure of the uncertainty in definition of the x component of the momentum of a particle, when Δx measures the uncertainty of its x coordinate. This principle can be derived directly from the wave picture. If the wave function describing a particle is to be so peaked that it serves to localize the particle within a distance Δx, it will be necessary to build up that wave function from a set of waves of differing wave-length, and the resulting uncertainty in wave-length, and hence in momentum, turns out[9] to be $h/\Delta x$.

A commonly used consequence of the uncertainty principle is the notion of *level width*. The uncertainty principle can be written in the form

[9] See *B1*, pp. 9–10. Thus, if we say that the nuclear particles have the mass M and are confined within a distance δ, their momentums must be expected to be of the order $\hbar/\delta$, and their kinetic energies, $\hbar^2/M\delta^2$. If the nuclear radius R or distance at which the specific nuclear forces first become important is 1.6×10^{-13} cm, the energy T is 20 Mev. The binding energy, computed from the measured mass defects, is on the average about 8.5 Mev per particle, so the average potential energy must be approximately 30 Mev. These relations give us a characteristic nuclear time t, the time required by a particle with the kinetic energy T to cross the distance δ; it is about 10^{-22} sec.

$\Delta E \Delta t > \hbar$, where Δt measures the uncertainty in the time at which a given system was known to have an energy E, uncertain by an amount ΔE. This relation also follows simply from a wave picture. It expresses the fact that what we describe as isolated systems are in reality only parts of larger systems with which they may exchange uncontrollable amounts of energy. We speak of an isolated hydrogen atom as being in a given "stationary state." This is only approximate; actually that atom has some chance of changing its state by emitting radiation corresponding, say, to a line of the Balmer series. The atom has some energy that couples it with the radiation field. The atom has a natural lifetime, around[10] 10^{-8} sec, which defines Δt and limits ΔE, the uncontrollable coupling energy with the radiation field; ΔE is approximately 10^{-6} ev. If we set up a discharge tube in which there are many hydrogen atoms in the same excited state, the energy of these atoms will be found to be spread over the range ΔE, and the minimum width of the observed spectral line is just ΔE. Ordinarily we describe the atom as an isolated system which has no chance to radiate; we specify that the atom is in one of its possible quantized states, each with a definite energy, angular momentum, and so on. But our description leaves out the possibility of decaying. It tries too sharply to cut the atomic system away from its surroundings. For a complete description of the excited atom, we must give an account of the possibility of decay—the natural lifetime. The number of atoms in a given state decreases with time like $\exp(-t/T)$, where T is the lifetime of the state. Then the natural width of the energy level in question, denoted by Γ, is given by the relation $\Gamma = \hbar/T$.

For atoms the natural width is always small compared with the spacing of the discrete levels. This assures us that our way of treating the atom as an isolated system, calculating its internal motion as though it could not radiate or change in any other way, is a good approximation. The correction required to take account of the possibility of transitions is small. For atoms the natural width, which is due to the motion of the electrons themselves, is small compared with the influence of collisions with other atoms and of the Doppler effect of the thermal velocities. However, even the total width of atomic levels is small. Atomic spectra are sharp.

[10] Heitler, *Quantum theory of radiation*, p. 110.

Not so with nuclear "spectra." We spoke of the resonance peaks observed in many excitation functions, which may be as narrow as a few volts or as wide as many hundreds of kilovolts. The nuclear states formed in a collision cannot by any means be well described as stationary bound states. Rather, we must recognize that such excited nuclei are very likely not to stay together but to break up into the products of disintegration.

The level width is a physical measure of the lifetime of a state for any mode of disintegration of which it is capable. If a given nuclear level can disintegrate through the radiation of γ-rays, or the emission of an α-particle or a neutron, one may speak of the *total width* of the state, given by the total lifetime for all these possibilities, and of the *partial widths*, which measure the probability per unit time of each separate process. The measurement and interpretation of level widths is a large part of the study of nuclear reactions.

5. Model of the Nucleus

We are ready to construct a model of the nucleus. By making models, calculating their quantitative implications and comparing them with experiment, we progressively obtain a model that has some essential connection with the reality of nuclear structure. Where does one start? We begin with what we already know, our picture of the atom, and try to modify it in accordance with the details of nuclear behavior. The atomic structure is well understood today; the atom consists of electrons maintained in

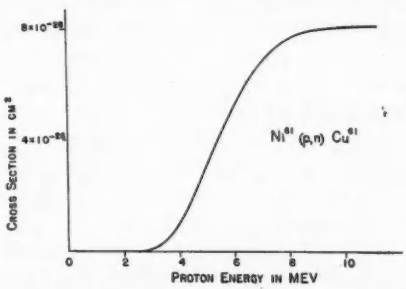

FIG. 3. The smooth rapid rise, with no evidence of level structure, to a constant cross section at high energy is typical of charged-particle reactions for nuclei of mass number above 50. The penetration of the Coulomb barrier increases until the energy exceeds the barrier height; then the cross section is of the order of the geometrical area of the nucleus. The levels are so dense and relatively so wide that no structure is manifested. This is a case perfectly appropriate for the statistical treatment.

stationary states in the electrostatic (and magnetic) fields produced by the positively charged nucleus and the moving negative electrons. The crucial feature of the model is the law of force: the Coulomb forces and the electromagnetic forces arising from relative motions of the charges govern the atom. The simple inverse-square law, verified on a macroscopic scale, and expressed in general terms by Maxwell's equations, describes how the atom is held together. In the atomic domain there are no specifically new types of force, none not known on a directly observable laboratory scale.

A. Nuclear forces

This is not the case with nuclei. Forces peculiar to nuclear matter set in when the particles are about 2×10^{-13} cm apart, as we know from careful scattering experiments with nuclear particles. These nuclear forces bind two protons together with 50 times the energy of their electrostatic repulsion at this distance. But we cannot observe these forces on any larger scale; nor is there as yet any general theory of them, such as the Maxwell equations for the electromagnetic field. From atomic spectra and the other experimental evidence, it was necessary to discover how the atoms were put together on the basis of known laws of force. But the nuclear problem is essentially more difficult; the study of nuclei must reveal not only how the component parts of the nuclear system are to be put together but also what laws of force govern their structure. It is by no means sure that nuclei will permit description in terms of potential functions and the rest of the mathematical machinery for such problems.

What do we know about nuclear forces? [11] The outstanding facts are that these forces are large and of short range. They bind protons with many times the energy of electrostatic repulsion; but, unlike the Coulomb force, they fall off, not gradually with distance of separation, but abruptly within a short distance. Two protons 1.3×10^{-13} cm apart experience strong nuclear attraction; at three times that distance apart they experience only the Coulomb repulsion. The nuclear forces depend on other variables besides the separation. They depend somewhat, but not much, on the kind of interacting particles; apart from the Coulomb forces involved, it seems a good approximation to regard proton-proton, proton-neutron and neutron-neutron forces as having roughly the same magnitudes. The strength of the forces depends on the relative orientation of spin; for example, proton and neutron are more tightly bound in the deuteron when their spins are parallel than when they are antiparallel. Nuclear forces seem also not to be central forces,[12] but to depend on the angle between the spins of the particles and the line of relative separation, like the force between two bar magnets.

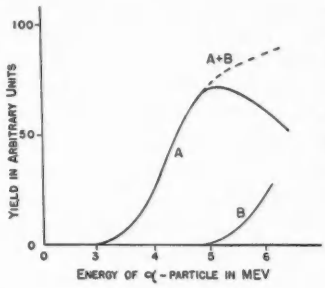

FIG. 4. An example of competition. Curve A: the proton yield of the reaction $N^{14}(\alpha, p)O^{17}$; it rises smoothly with the barrier penetration until the threshold of the competing reaction at 5 Mev is reached. Curve B: the competing reaction, $N^{14}(\alpha, n)F^{17}$, yields neutrons. The total cross section continues to rise slowly.

This so-called "spin-orbit" force was indeed predicted by the current theory of nuclear forces, and is consistent with the recent discovery that the deuteron has an ellipsoidal and not a spherical distribution of charge. The spin-orbit force has the effect of preventing a sharp division of angular momentum into intrinsic, or spin, angular momentum and orbital angular momentum. The spin-orbit force acts to convert one form into the other.

B. The drop model

What kind of nuclear model can be constructed in the light of this qualitative knowledge of nuclear forces? Again we look to the atom for suggestions. In the atom each electron moves in the average force field of the nucleus and the other moving electrons. The forces are long range, varying slowly with distance, and hence it matters little if we neglect the fact that other electrons sometimes approach closely to the electron we are considering. We can study the motion of each electron separately, taking account of the motion of the others only in a general way. Thus, even with scores of electrons

[11] *B2*, sec. 76C; Plesset, Am. J. Phys. **9**, 1 (1941).

[12] Christy and Kusaka, Phys. Rev. **55**, 665 (1939).

in an atom such as lead, the problem is relatively simple; we fix on the detailed motion of each electron in turn, allowing for the others only as they influence the average field felt by the electron under study. This approximation, called the *Hartree approximation*, is first rate for atoms and gives a fine description of the loose, smooth, open structure of the atomic shells. But it is completely inappropriate for nuclei. In nuclei the force on each particle depends very much on the position of the other particles of the system: If some other particle is very close, the interaction is strong; if it is just a little farther away, there is no interaction at all. Instead of a miniature solar system, we are dealing with a miniature drop of water. The component particles jostle one another constantly. Continual and rapid transfer of energy from particle to particle of the system is the rule, and not the exception. There is no well-marked center of force that determines the motion in a general way. It would be most misleading to try to peel off the motion of each particle in turn and average over the effect of its neighbors. Instead of a slow, smoothly varying mutual interaction, which can without much error be replaced by a constant average, the plot of the interaction energy between one nuclear particle and the rest of the nucleus as a function of time is a jagged and peaked function. To average over such a motion would be to conceal its essential features.

Except for the nuclei of smallest mass, a nucleus has no shell structure of loosely coupled particles. For the two-particle deuteron, which is among nuclei what the hydrogen atom is among atoms, the notion of a central potential clearly has some sense. And indeed, for all nuclei up to about neon, the shell structure still plays some part, and the Hartree model and related approximations are useful. But the typical nucleus for our discussion has 50 or more particles, and for it, the separate motion of the nuclear particles is only in a very general way accessible to study. The decisive feature of nuclear structure is the extreme ease with which energy is interchanged between the densely packed particles of the nucleus, and hence the "stationary states of a nucleus must correspond to some quantized collective type of motion of all its constituent particles." The collective motion of the whole nucleus, and not the individual states of the particles, is decisive for nuclear behavior. Indeed, the model of a nucleus as a drop of matter of very large density and electric charge, treated as a thermodynamic system by methods that take into account the quantum-mechanical effects at the distances and wave-lengths involved and also the relatively small number of degrees of freedom, leads to our most satisfactory quantitative conclusions.

How does this model influence our picture of nuclear reactions? Again let us recall the case of atoms. When an electron (or proton) collides with an atom, it is less likely to be deflected by the field of any single atomic electron than by the average field of the whole atomic structure. Most often it will collide elastically, thus giving up no energy. When energy is transferred, usually only one of the atomic electrons will be excited to a higher energy level, the others being left unaffected except by the slight change in the average field. The colliding particle will pass through the atom in a time having the order of magnitude of the atomic diameter divided by the speed of the particle. For medium-energy collisions this time is of the order of the characteristic orbital period of the atomic electrons themselves, and relatively slow disturbances of the atomic state—for example, the emission of a light quantum—will be improbable.

Contrast this with our picture of the nucleus. Since nuclear forces are short range, the spacing of nuclear particles and the range of nuclear forces must be quite comparable. A colliding particle cannot pass through the nucleus without being influenced very strongly by the force fields of all the nuclear particles it encounters. Upon entering the surface of the nuclear matter, it transfers some of its energy to the surface particles, and then continues on, all the time transferring energy to the nuclear particles. The result is that the initial kinetic energy of the incident particle is soon spread over the many particles, thus leading to an excited state for their collective motion. But no single particle is likely to have enough energy to escape from the system. Only after many nuclear collisions will some particle chance to collect enough energy to escape. This particle need not be of the same kind as the one that entered; it may not have

collected as much energy as the incident particle brought in, and it may leave the residual nucleus in an excited state, to "boil off" still another particle or a γ-ray before settling down to the normal ground state. An elastic collision, in which the whole of the energy brought in gathers on a particle just like the incident particle, clearly will be infrequent, once the nuclear surface has been entered. The time elapsing before any particle escapes from the nucleus will be very long compared with the characteristic collision time; for many collisions must occur within the nuclei, and the energy must spread and reconcentrate. In so long a time even very slow processes, such as γ-radiation, will be important. This long time during which the particle and target are combined to form a quasi-stationary compound nucleus is the key to the Bohr picture of nuclear processes; and it already suggests answers to the experimental results we mentioned earlier—the long time associated with reactions. The reaction $T(i, p)R$ is not simply a direct transition from a state representing the nuclei T and i to one representing p and R. The reaction has two steps: the formation of a compound nucleus, and the disintegration of that compound into the products of reaction. The degree to which these steps are independent and the duration of the compound state will be problems for our study.

Since the nucleus must be treated by quantum-mechanical methods, we will have to describe the states of the compound nucleus as quantized levels having a certain energy which will be more or less well defined. Each state of this compound nucleus will have a level width that is inversely proportional to the rate at which the state disintegrates. We shall denote the width of the ith energy level by Γ_i, and shall usually express this in electron volts. These energy levels are connected with the phenomenon of resonance. If the energy of the projectile is such that the combined energy of projectile and target is equal or nearly equal to the energy of one of the quasi-stationary states of the compound nucleus, then it is very probable that the compound nucleus will be formed, and subsequently will disintegrate in any way available to it. This is the familiar resonance found in so many wave phenomena. Resonance leads to a critical dependence of yield on energy and, hence, to the peaked excitation functions we have described in SEC. 4. It is especially marked in cases where the wave picture of the collision is found most appropriate, as for slow neutrons and low energy γ-rays. The theory of nuclear reactions from the point of view of resonance and near resonance is mathematically similar to the treatment of the coherent and Raman scattering of light, which gives a theory of the optical refractive index in terms of the atomic energy levels. Hence the nuclear theory is by analogy called the *dispersion theory of nuclear reactions*. We shall later connect this picture with our simple mechanical account of the formation of the compound state and the statistical treatment of its disintegration.

C. Levels and level widths

What are these almost stationary states of the nucleus and how are they spaced? Just as the level diagram of an atom is fundamental for an understanding of the atom's spectrum, so the level diagram of the nucleus is fundamental in the study of reactions. Atomic energy levels can be calculated by solving accurately the equations describing the wave functions of each electron in turn, in the known force field. This we cannot do for nuclei. But the chaotic, close-coupled, collective motion of the nuclear particles makes possible a statistical investigation based on our model.

For the smaller nuclei, the individual characteristics of the nuclear levels will play an essential part, and statistical treatment indeed will be unrevealing. But for nuclei of medium and large mass number, it is fruitful to think of them as thermodynamic systems, with a "temperature" —an average energy per degree of freedom—an "entropy," and so on. Then level density can be calculated.

In an atom the electrons move in well-defined shells, each shell experiencing a force quite different from the others because of the long range character of the Coulomb forces; thus the K electron energy levels in a heavy atom have 10^4 times the binding energy of the valence levels, and the resulting level diagram has widely separated bands of a few levels each. Contrast this with the case of the nucleus where the particles move together, no group of them experiencing a force much different from that of any other set. The energy of the whole system can be distributed over the various particles in many ways, and for only a very few of these will much energy be concentrated on any single particle; the probability of such concentration is small indeed. On the other hand, the number of different energy levels—stationary states of the whole system—will be very large. The level diagram of a nucleus will contain many closely

spaced levels, without very marked bands or empty spaces; the change of spacing with energy is smooth. Even when the stationary state is no longer really a steady state—that is, when the energy is so large that there is some probability that the system will disintegrate into a residual nucleus and a free particle—the level spacing and the properties of the levels will not alter qualitatively. The level will no longer be sharply defined in energy but will possess some width. If the energy is high enough, the width of the levels will be greater than their spacing, and the level structure will begin to disappear into a continuum; but even here the chance of disintegration is so small that the wave function describing such a highly excited compound nucleus will not be greatly different from that applying to its lower lying states.

Let us make these ideas precise.[13] Let E represent the total excitation energy of such a nuclear system, and let S be the entropy, defined as usual as the logarithm of the thermodynamic probability; that is, $S=\ln \omega(E)$, where $\omega(E)$ is the number of energy levels in a given range of energy at E. Then, as usual, $S(E)=\int_0 dQ/T(E)$. Here Q is simply the total energy, and $T(E)$ is, like kT of ordinary statistics, a function that measures the average energy per degree of freedom. Nuclei are systems having very low "temperatures"; the excitation energy is small compared with the total binding energy. Since most of the energy of a nucleus is its "zero-point" energy, we cannot expect classical statistics to hold; all degrees of freedom are not uniformly excited. Suppose that the individual modes of excitation have characteristic frequencies ν_i and, therefore, energies $h\nu_i$. To obtain a simple model, let us assume that all modes of vibration up to those with frequency $\bar{\nu}$ such that $h\bar{\nu}=kT$ are equally excited while those of frequency exceeding $\bar{\nu}$ are not excited at all. Then we can put the number of modes excited as proportional to the energy range T. But the total excitation energy is the product of the average energy per degree of freedom and number of degrees of freedom excited. Thus we can write $Q=aT^2$ and, by integrating and using the definition of the entropy, obtain $\omega(E)=C\exp(aE)^{\frac{1}{2}}$.

This rough derivation is given more weight by the fact that the result agrees with that for better models. For example, a Fermi gas involves the same expression, $Q\sim T^2$, and in metals, where the forces between the individual particles are not negligible, the exponent is not much different. The calculation made by Bohr, which makes use of the surface-tension oscillations of a drop of liquid as the model for the modes of vibration, gives very nearly the same result. Such models give as the dependence on mass number, $a\sim A$.

[13] *B7*, sec. III.

The width of levels, at least for some processes, such as the emission of neutrons, can be calculated in just this way, by applying thermodynamic analogies, here the process of evaporation and condensation of vapor molecules. Thus the value of the neutron evaporation width for a neutron of escape energy E is found to be proportional to $\exp(-E/kT)$. The distribution of energy is a Maxwell distribution appropriate to the nuclear temperature T. Not only in metaphor does one speak of the nucleus "boiling" off neutrons! This effect is responsible for the fact that the neutrons which are released from compound nuclei do not often take off all the energy available but only the average temperature energy, leaving the nucleus in a compound state of lower energy—or temperature—from which, indeed, a second and possibly a third neutron can boil off. These are successive, independent processes. This course of neutron emission means that neutrons with energy much higher than the lowest excited level will be inelastically scattered; that is, they will be captured and a neutron of lower energy emitted, followed by radiation to bring the residual nucleus down to its ground state.

Charged particles, as well as neutrons, may be treated in this same way. Here the energy of release will be larger than the temperature energy, because the proton or α-particle emitted will experience the Coulomb repulsion of the nucleus as soon as it reaches the end of the nuclear force range, and will slide downhill in the electrostatic field, gaining energy as it goes. If the excitation energy is not high enough, however, to expel the charged particle with energy greater than the height of the Coulomb barrier, then the boiling off of protons will be unlikely compared to the neutron evaporation, in the same way that reflection by the Coulomb barrier determines the slowness of α-particle disintegration of natural radioactive bodies. Except where α-particle emission releases a great deal of energy, there are no cases of charged particle emission in the nuclei above middle values of atomic number.

The statistical treatment cannot be complete because of the lack of a detailed nuclear model. The difficulty of finding the temperature of the nuclear system, and the small number of degrees

of freedom (compared with a macroscopic object) make such thermodynamic arguments at best semiqualitative. But they are, in their domain of application, the best description of the nucleus we are likely to have for a long time.

D. Limitation of the statistical treatment

When are statistical arguments inapplicable? Obviously when the details of specific nuclear states are involved, as will be the case when the nucleus is so light or the energy of excitation so low that we deal with only one or two levels at a time. This is the region of the interesting resonance properties which we must discuss in SEC. 7. A glance at the complex excitation function of F^{19} (Fig. 2) will reveal how inappropriate a statistical description would be. The occurrence of well-defined, discrete levels is closely connected with the importance of the wave picture. For slow incident particles, for γ-rays and for charged particles that have kinetic energies lower than the energy of the electrostatic barrier, the wave-lengths will be at least comparable with the dimensions of the nucleus. Then "diffraction" will be important, and we shall not be able to define the nuclear surface or the motion of the individual particle in any clear way; we shall have to use characteristic wave notions, and resort to the ideas of resonance and the dispersion theory. For the region of extreme wave-lengths, the results will be in excellent agreement with experiment. In the region where individual resonance levels are important and detailed study is necessary, present general knowledge is insufficient but apparently not inconsistent with experiment. But even in the high energy, small wave-length region our statistical treatment does not always work. Statistical calculation always involves the assumptions of statistical independence, and the absence of special wave effects such as interference or coherent scattering. We must be able to treat separately the formation of the compound state and its disintegration. The model described makes it plausible that the chaotic mixing of the incident particle and the target into a compound state will make the system "forget" its original condition, lose all phase relations between the wave functions and so make interference effects negligible. This is perhaps not always true; sometimes the nucleus may "remember" the way it was made, and will preserve the phases of the incident wave function. A still different case is elastic scattering, in which the incident particle is not changed in kind or energy. Here the incident particle never merges with the nuclear matter, and more careful treatment is needed, taking account of diffraction effects. Neither the statistical notions nor the simple dispersion theory should be thoughtlessly applied.

6. THE COURSE OF NUCLEAR REACTIONS

Let us look at the course of a typical reaction. At first we will use the statistical picture. This means that we must restrict ourselves to processes where many states of the compound nucleus are involved, as will always be the case when the heavier nuclei are bombarded with charged particles from a Van de Graaff generator or a cyclotron. The experimental spread in the incident energy is then much greater than the level spacing. This will be true generally when the excitation energy exceeds 2 Mev for nuclei with $A>50$, because the widths of the nuclear levels are then greater than their average spacing. Then we can think of the compound state as having a continuum of energy levels, like an ionized atom. Except for special effects such as elastic scattering, mentioned previously, our statistical treatment will be adequate, because all resonance effects due to the properties of individual levels will be averaged out. This is in general true for all nuclei heavier than, say, argon.

A. Steps in the reaction

We will use the fundamental idea of Bohr that the reaction takes place in two steps: (1) the formation of the compound nucleus, (2) the independent disintegration of that compound nucleus. Consider the reaction $T(i, p)R$. The cross section σ_p for the reaction is $\sigma_i(\epsilon)D_p(E)$. Here σ_i is the cross section for formation of the compound state by bombardment with an incident particle of energy ϵ; $D_p(E)$ is the relative probability of disintegration of the compound state into the residual nucleus R and product p, when the excitation energy of the compound state is E; and E is the sum of the kinetic energy of incidence and the binding energy of i in the

compound state. In writing the cross section as the product of two separate functions σ_i and D_p, we assume that the compound state will disintegrate in a way independent of its manner of formation. But this is not true; actually the wave function which describes the compound state is built up of wave functions representing the various possible excited states at this energy. These waves will have definite phase relations depending on the details of formation. But our method is based on the ability to neglect these details because so many states are involved that the phase relations are distributed at random. Putting it another way, the energy distributes itself so rapidly among all the particles that before the reaction is completed the details of formation have become unimportant. This natural consequence of our model is a good approximation in the processes we are now considering. We can still further break up the reaction by splitting σ_i, the cross section for formation of the compound state, into two factors, $S_i(\epsilon)\xi$. Here $S_i(\epsilon)$ is the cross section for reaching the nuclear matter, a function that depends only on effects outside the reach of the specific nuclear forces; and ξ is called the *sticking probability*, the probability that the incident particle will share its energy with the target nucleus once it reaches the nuclear surface. (Then $1-\xi$ is just the probability of elastic scattering.) This separation is, of course, an idealization; the sticking probability will, in fact, depend upon how the surface is reached, and the surface itself cannot always be well defined. But we introduce ξ in order to throw our ignorance into a single factor which depends upon the nucleus itself. The dependence of ξ on energy and reactants will test our model.[14]

From this separation into steps we get some general results. For large bombarding energies the wave-length is small and the particle picture accurate. Then the cross section for reaching the nuclear matter must be the geometrical cross-sectional area of the nucleus, or $\sigma_i \cong \pi R^2$. The probability for forming the compound state is then $\pi R^2 \xi$. The value of ξ must be close to unity, since, for high energy, the projectile is almost certain to "stick." Once formed, the state must disintegrate in some way. The total cross section for all processes (barring elastic scattering, which does not give rise to formation of a compound state) must be $\sigma_{\text{total}} = \pi R^2$. If we define the widths appropriately, either by a suitable average, or by fixing our attention on any special state, the cross section for a particular product is just $\sigma_{\text{total}}\Gamma_p/\Gamma$, where Γ is the total width summed over all possibilities. This formula is the nub of the Bohr picture. Its use depends upon the correctness of dividing the reaction into independent processes of formation and disintegration of the compound state, running in free competition, without correlation between modes of formation and breakup. It already explains the constant high energy cross section, of the order of the nuclear area, and the possibility of much smaller cross sections for special modes of disintegration (Fig. 3).

B. Reaching the nuclear surface

1. The centrifugal barrier.—Let us consider in more detail the cross section S_i for reaching the nuclear surface, which we shall call the *contact cross section.* We have defined it so that it does not depend on nuclear forces at all, but only on the external fields of the nucleus. What fields act on an incident particle before it strikes the nuclear surface? If the projectile has no charge and is aimed directly at the nucleus, it will experience no force at all. If the particle description holds good, as it does for a fast neutron, the contact cross section is then πR^2, where R is the nuclear radius defined as the distance where the specific nuclear forces first come into play. Such a particle will strike the nuclear matter if its distance of closest approach, measured from the nuclear center, is less than R. But a particle moving by the nucleus has relative angular momentum. Classically, if its distance of closest approach is d, a particle of mass m and speed v has an angular momentum $mv \cdot d$. The rotation of the whole system about its center of mass leads to a centrifugal force on the projectile. Classically, particles strike the nuclear matter whenever they come nearer the center than the distance R. But, for a given speed, particles of angular momentum larger than mvR never come near enough; centrifugal force keeps

[14] A theory of the sticking probability has been begun in an interesting paper by H. A. Bethe, Phys. Rev. **57**, 1125 (1940).

them away. When the wave picture is appropriate, the distance of closest approach has no sharp meaning; the waves diffract around the obstacle. But the effect of the centrifugal potential is still to reduce the probability that an incident particle of large relative angular momentum will strike the target. Particles with angular momentum l, measured in the natural unit $\hbar$, tend to concentrate at the distance $l\lambda$ from the center. This is just the classical distance of closest approach for such a particle.

It is worth while to discuss the angular momentum in more detail.[15] The orbital angular momentum L is mvR. Here mv is the relative momentum of the colliding particles and R the distance of closest approach. Angular momentum has the dimensions ML^2/T, the same as those of $\hbar$, which is in fact the natural quantum unit of angular momentum. If we write $\hbar/mv=\lambda$, then $L=d\hbar$, where d is the distance of closest approach measured in units of the wave-length. When d is fairly small, the complete wave-mechanical theory shows that we must quantize the relative orbital angular momentum. Since d must be an integer, $L=0\hbar$, $1\hbar$, $\cdots$.

The waves corresponding to orbital angular momentum $0\hbar$, $1\hbar$, $2\hbar$, $\cdots$ are called s, p, d, $\cdots$ waves, respectively. These wave functions have their greatest amplitude in the region around the classical distance of closest approach for each value of L. The plane wave which represents a steady stream of particles of a given mass and velocity contains the spherical waves which represent particles of all orbital angular momentums around the target. The plane wave can be specified by giving the direction and magnitude of the momentum vector $m\mathbf{v}$. Or we can give the fraction of particles with each different L value, and the magnitude of the momentum. Since the orbital angular momentum is a constant of the motion for the particles of the beam, this division into partial waves is a useful method in collision problems. The particles of the beam that make a nearly direct hit ($d=0$) are the particles described by the s wave. Particles that hit on the average about one wave-length away are p wave particles, and so on.

Besides the angular momentum of orbital motion, protons, neutrons and electrons have an intrinsic angular momentum, called *spin*, which is just $\frac{1}{2}\hbar$ in magnitude. Spin and orbital angular momentum are vectors, and can be combined and resolved into components, following the rules of the so-called "vector model" of atomic spectra. All components have values that are integral or half-integral multiples of the natural unit $\hbar$. For example, the nuclei, which are systems of moving neutrons and protons, have a total resultant angular momentum J; J is made up of the intrinsic angular momentum of the heavy particles and of the angular momentum of their relative motion within the nucleus. For stable nuclei, the magnitude of J runs from 0 to as high as $(11/2)\hbar$. As we would expect from the rules for combination, J is a half-integral multiple if A, the total number of particles, is odd; an integral multiple if A is even. For the α-particle ($A=4$) $J=0$; for the deuteron ($A=2$) $J=1$; for the Li nucleus, $J=\frac{3}{2}$. These values are consistent with the rules for combination and the facts that the spin per particle is $\frac{1}{2}\hbar$, and the orbital momentum has only integral values.

2. The Coulomb barrier.—The only forces acting on neutrons before they touch the nuclear surface are the centrifugal forces arising from their orbital motion. But protons, deuterons, α-particles—all positively charged nuclear projectiles—will experience, in addition, the electrostatic repulsion of the nuclear charge. The particle will move toward the nucleus until the potential energy of Coulomb and centrifugal repulsions is equal to the kinetic energy of bombardment. Then its velocity will be zero. Classically, it would turn back and slide down the potential hill. Only a particle with initial energy larger than the maximum potential energy could penetrate to the surface of the nucleus. The maximum potential energy for a particle of charge ze, mass m and angular momentum l is just[16] $(zZe^2/R)+\hbar^2l(l+1)/2mR^2$ in the field of a nucleus of charge Ze and radius R. This energy is called the *barrier height*. As a particle of energy less than the barrier height approaches the nucleus, its velocity decreases under the influence of the repulsion. Its wave-length goes up as its velocity goes down, for $\lambda=\hbar/mv$. Clearly it will not be possible to apply the particle picture in the region of the turning point, where the wave-length becomes infinite. Here quantum effects come in, in an essential way. The particle diffracts through the potential barrier in exactly the way that the α-particle tunnels through the barrier of a uranium nucleus in α-decay. The particle has some probability of reaching the nucleus, a probability that decreases as the height and width of the barrier increase in comparison with the kinetic energy and the wave-length of the incoming particle. The probability for penetration can be computed accurately for a given potential, and quite approximately when one uses a Coulomb potential, simply cut off at the distance R. In this penetration probability lies the explanation of the nearly exponential rise of the excitation function from zero that is observed

[15] A helpful account is given in *B6*, pp. 47–50.

[16] *B2*, sec. 72, and *B8*, p. 132, give details and graphs.

in many reactions, for example, in $Li^7(p, \alpha)\alpha$. As long as the contact cross section is the most rapidly varying factor, which is the case when the energy is far below the barrier height and no special resonances occur, the Gamow factor will govern the course of the excitation function. This will be generally true for low-energy, charged-particle reactions.

C. Disintegration of the compound state

We have been limiting our discussion to cases where the compound state can involve the combination of many different energy levels, so that features of individual levels are not important. Any properties that must be conserved throughout (of which the total angular momentum is the best known) will hardly influence the reaction in this limit, because plenty of states are available that will satisfy any conservation conditions. This thorough mixing is the consequence either of poor definition of the energy of the incident particles compared to the level spacing or, more generally, of the fact that the natural width of every level is greater than the average distance to the next. Both will be true for nuclei with mass numbers A exceeding about 50 and incident energies of 1 Mev or more. In such cases the compound state, once formed, will disintegrate in a way that depends solely on the competition between all the processes for which enough energy is available. Again we except the elastic scattering—disintegration resulting in the re-emission of the incident particle with the incident energy.

The total probability for the process emitting particle p is just $D_p=\Gamma_p/\sum_j \Gamma_j$. Here $\Gamma_p=\sum_n \Gamma_p(E_n)$, where Γ_p is the total width for emission of particle p, whatever the resulting energy E_n of the residual nucleus may be, and $\Gamma_p(E)$ is an average over all states in the energy range near E; the influence of all other properties which describe the compound state is averaged out.

We will estimate Γ_p by the general methods of statistical mechanics. We shall consider the compound nucleus in its several excited states to be in thermal equilibrium with a collection of all the various particles which can be emitted by the compound. In equilibrium, the probability of every process must be equal to the probability of the process exactly reverse to it. This equality holds only when we forswear the possibility of detailed knowledge about the compound state and are willing to use the ideas of equilibrium. Enough has been said to show how satisfactory the method is in the case at hand. Our result will relate the T's to the contact cross section for the reverse process, which we can easily calculate, and to some averaged properties of the compound state. Thus the Coulomb barrier which reduces the contact cross section for bombardment by a charged particle also acts to reduce the level width for emission of a charged particle from a compound state. The method runs parallel to the calculations for ordinary evaporation and leads to simple formulas for the cross section.

Let us sketch the steps of such a calculation.[17] We shall find the probability for the formation of a compound nucleus by the collision of a given particle of mass m and energy $\epsilon_p=\frac{1}{2}mv^2$ with the *residual* nucleus in the state α. The cross section for this process is just the formation cross section for the compound C, with excitation energy E, in which p is bound with binding energy E_p, from p, and R_α, with energy E_α. This is $\sigma_{p\alpha}=S_p(\epsilon_p)\xi_p$, with $\epsilon_p=E-E_\alpha-E_p$. Then the number of nuclei C formed per second per unit density of nucleus R_α is $\sigma_{p\alpha}\cdot v_p$. But the compound nucleus can be formed in any of the many states $\omega_C(E)dE$, where $\omega_C(E)$ is the number of states per unit energy at the energy E for the compound nucleus. Then the probability per state is $\sigma_{p\alpha}v_p/\omega_C$. This must be equal in equilibrium to the probability for the reverse process—the disintegration of nucleus C into particle p and residual nucleus. We need the number of states of the residual nucleus per unit energy, ω_R. Now the total width Γ_p for any energy of the residual nucleus is found by summing $\Gamma_{p\alpha}$ over all energies and all angular momentums. The free particle also can be emitted into many states, corresponding to the different directions in space and different orientations of spin. The number of states available to the free particle is equal to the number of spin orientations, $(2s+1)$, multiplied by the volume in phase measured in units of h^3. For a free particle of momentum k the number of states per unit volume and energy is then $4\pi k^2/(2\pi\hbar)^3\cdot dk/dE=4\pi mk/(2\pi\hbar)^3$. Putting these ideas together,[18] and writing the sum as an integral, because the states are spaced so narrowly, we obtain

$$\Gamma_p=(2s+1)m/\pi^2\hbar^2\omega_C(E)\cdot\int_0^{E-E_p}d\epsilon\epsilon S_p(\epsilon)\xi_p\omega_R(E-E_p-\epsilon).$$

Here S_p is known, ξ_p is estimated and the level densities of the nuclei can be gotten from our model. The energy distribution of the escaping particles is then $I(\epsilon)=I_0\epsilon S_p\xi_p\omega_R(E-E_p-\epsilon)$.

This is the end result of the evaporation-equilibrium model of the reaction. Even though the level density is

[17] *B7*, sec. II.
[18] *B9*, p. 546.

only roughly known, the relative probability I/I_0 is fairly accurate, since the various ω_R's usually change in similar ways for the various models. These formulas will be applicable in our range of nuclei $A>50$ and about 10^6 ev excitation. The level densities and the sticking probabilities will show little individual variation in this domain.

D. Competitors

What are the products of nuclear reaction that compete for emission? We can classify them as follows:

1. Heavy particles: neutron, proton, α-particles and so on.—No α-particles are found except in the reactions of nuclei of mass number less than 20, where the Coulomb barrier is small so that the emission of a highly charged particle is not too improbable, or in the very heavy nuclei of the radioactive series where the emission of an α-particle releases a great deal of energy. When the heavy particle emitted is the same kind of particle as the projectile, the process is called *inelastic scattering*. When, in addition, it has the same energy, the process is *elastic scattering*, which is a kind of "unsuccessful" reaction; the compound state is not formed.

2. Light particles: electrons, positrons and positron-electron pairs.—The emission of light particles can be easily disposed of.[19] The study of β-rays, both positive and negative, forms a large part of the data on reactions. This is because the residual nuclei of a reaction are very often β-active, and can be detected by their activity when no other means are adequate. But the shortest lived β-activities have lifetimes of about 1 sec, whereas the nuclear reaction times are at most about 10^{-11} sec. It is natural, then, to separate the β-disintegration from the nuclear reactions themselves, and to consider it a part of the study of stable nuclei. The extreme slowness of β-decay is the result of the extraordinary smallness of the coupling energy between protons and neutrons and the "field" of light particles which they can emit. While the nucleus readily emits radiation and heavy particles, even though slowly compared to the characteristic nuclear time, it is only with phenomenal rarity that it emits a β-ray. The number introduced by Fermi to describe the β-coupling—an analogy to the charge as a description of the coupling of a charged particle with the electromagnetic field—is only 10^{-13} in atomic units ($\hbar=m=c=1$). We shall not discuss β-emission at all, but shall treat β-radioactive states of nuclei as essentially stable states, the end-products of reaction.

3. Radiation: γ-rays.—By *capture* is meant the process, T (heavy particle, γ-ray) R; that is, a process in which a target T is bombarded by a heavy particle, γ-rays are emitted and a residual nucleus R is produced. Radiation is a very frequent competitor of the heavy particles. It is typically emitted after a compound nucleus has given up some, but not all, of its excitation energy to a heavy particle. Then γ-rays are emitted until the nucleus has cooled to its normal state. This emission proceeds without, of course, changing either Z or A; only the state of motion of the nucleus is changed. When there is insufficient energy available for the rearrangement into a residual nucleus R differing by one or two in Z or A, γ-rays have no competition.

Radiation is slow compared to the time of intranuclear collisions. Even in atoms, radiation is slow compared with orbital times because of the relative smallness of the coupling of charge to the electromagnetic field, the dimensionless number α describing this being $\alpha=1/137$. But in nuclei the close-packed nature of the motion slows the radiation down still more, just as it slows particle emission because of the infrequent concentration of energy.

In an atom the positive charge is concentrated in a massive nucleus, and the negative charge is spread over the relatively light electron shells. When a single electron is excited there is the possibility of quite unsymmetrical distribution of charge, which can give rise to strong radiation whose wave-length is not too great as compared with the distance of charge displacement. So atoms radiate dipole radiation almost entirely. For nuclei, the situation is quite different. The mass and charge reside in the same particles. Perhaps the protons crowd a little to the edge of the nuclear drop, but the effect is small; the electrostatic repulsion is small compared to the nuclear coupling energies. The nucleus behaves like a drop of nearly uniform charge density and mass density: there is no chance for the charge-center to be much displaced relative to the mass-center. In such a drop with a highly symmetrical arrangement of charge, radiation is impeded for

[19] *B3*, chap. II.

any waves whose wave-length is not short enough for them to take advantage of the very small-scale variations in charge and current density. So γ-radiation of wave-length exceeding 10^{-13} cm and energy less than 20 Mev may be slowed down very much indeed. The nucleus radiates like a rotating and oscillating drop of nearly uniformly charged matter. In fact, quantitative calculations based on this model give considerable insight into the level widths for γ-radiation.

The great complexity of nuclear γ-rays (remember the example of fluorine) provides a rich field for studying the nuclear energy levels of both light nuclei, where individual levels of considerable energy difference are involved, and heavier nuclei, where the notions of the drop model can be tested.

7. The Dispersion Theory

The statistical theory of nuclear reactions, based on the Bohr model of the nucleus, is plausible and fruitful as a general account of nuclear phenomena. But in spite of its naturalness it is new; despite its generality, it leaves out many of the most beautiful and instructive phenomena of the nuclear domain, especially the most carefully studied reactions in light nuclei.

Some six years ago the experiments on slow neutron scattering carried out by the group at Rome gave the impetus to a great expansion in the data and the ideas we had concerning nuclear matter. Fermi and his co-workers discovered the marvelous selective nuclear absorption and scattering of low energy neutrons. The conception of a tunnel effect, in which α-particles leak through the Coulomb barrier, together with the long studied scattering of α-particles, provided an apparently satisfactory picture for the neutron processes, very different from the Bohr model we have described. The picture was that of a potential well, a force field made up of the total effect of all the many nuclear particles in whose combined field the incident particle moved. In α-decay, the particle shuttled back and forth across the potential well, until, once in a while, it would happen to tunnel under the barrier. For scattering, the nuclear forces supplied a potential well. For the resonances observed with both charged particles and neutrons, one thought of the incident wave as penetrating the barrier (for neutrons, the barrier was not present) and standing in the potential well; when the wave-lengths were such as to fit exactly into the well and make a permanent standing wave, a resonance level existed. The multiple reflection, with constructive interference, back and forth across the well, built up the wave function strongly, and the absorption of the neutron (or α-particle) grew rapidly at energies around several well-defined values. This gave a good account of such reactions as $Mg^{24}(\alpha, p)Al^{27}$ or $F^{19}(\alpha, p)Ne^{22}$. It was a view quite analogous to the description of the absorption of a sound wave by a Helmholtz resonator where, for definite wave-lengths, the confined air volume of the resonator acts as an excellent absorber.

This one-body model, in which the incident particle moves in a well-defined, if unknown, field of force, seemed very reasonable indeed.[20] However, one serious flaw was revealed by the slow neutron resonance work. A Helmholtz resonator not only absorbs the sound energy but, as the resonance frequency, re-radiates very easily; the intensities built up cause a strong re-emission. Likewise, we should expect the scattering of neutrons at resonance to be marked, even more so than their capture by dropping to a lower level in the potential well. But experiment soon showed that capture occurs *without* any considerable increase in scattering.

This led to the formulation of a view that bridged the gap to the many-body model of Bohr.[21] On this view the process took place through an intermediate state. The energy of the initial state of incident particle and target coincided at resonance with that of some other state of the whole system, a state in which, for example, a different neutron had the energy of excitation, and the incident one was bound. The intermediate state was not truly stationary, but itself decayed into a new state of almost the same energy. The final state represented the emitted particle and the residual nucleus. This description is parallel to the theory of the dispersion of optical light; in optical dispersion the incident quantum is resonant with some excited level of the atom, a level whose character is

[20] See G. Gamow, *Atomic nuclei and nuclear transformations*, chap. V.

[21] See *B1*.

modified by the possibility of emitting quanta in a return, not only to the initial state, but to entirely different final states. The theory applied to the nucleus was therefore called the *dispersion theory* of nuclear reaction. The observed sharpness of resonance in, say, F^{19} meant a very small damping—slow decay—of the intermediate state; and the many slow-neutron resonances observed in a small energy range among the various isotopes suggested a close spacing of the nuclear compound levels at moderate excitation energy. This led to the picture we have discussed, first clearly formulated by Bohr early in 1937.

A. The dispersion formula

The dispersion theory begins with a viewpoint which is opposite to that of the statistical theory (SEC. 5C). Instead of looking to the complexity of the motion, making arguments based on the very general ideas of thermodynamics, and refining these in the direction required by the quantum effects which come in at the small distances involved, the dispersion theory starts by asserting the possibility of a complete description of incident particle and target nucleus by a single, even if unknown, wave function. It ascribes other wave functions to the various possible final states—residual nuclei plus the products of all occurring kinds and energies. All these functions represent the initial and final stages of the reaction; that is, they describe the initial system of target nucleus, with incident particle far removed, or the final system of product nucleus with emitted particle far removed. To the compound stage is ascribed another set of wave functions, one for each possible level. These levels of the compound stage are not exact stationary states. They decay slowly; the amplitude of the wave function varies with time as does that of a damped oscillator, with damping constant $\Gamma_i/\hbar$, where Γ_i is the level width, which represents the necessary lack of definition of the energy of the compound system. The initial and final states, on the other hand, represent quite different stationary states of the whole system, and do not tend to mix with each other. A proton of a given energy plus a calcium nucleus in its ground state is quite different from a neutron of a given energy plus a potassium nucleus in some excited state. But the wave function of the compound stage can be made up of functions describing such initial and final states; for the compound nucleus is formed from the one, and decays into the other. Thus the forces at the target nucleus can "mix" some of the final-state wave functions with that of the initial state to form the compound, which may then break up. When the energy of the initial state coincides, within the level breadth, with that of some compound level, mixing is especially strong, and the resultant wave function which describes the whole system will contain a good deal of the final state, the state representing the products of the reaction. The mathematical problem can be solved. It leads to formulas that can be applied under proper circumstances and that reduce in the appropriate limit to those derived from the statistical treatment.

The mathematical problem is exactly like that of a tuned circuit and an incoming radio wave. The circuit responds very strongly when its natural frequency is that of the incoming wave. The sharpness of this resonance—the degree to which agreement between wave frequency and tuning is necessary—is measured by the natural damping of the tuned circuit. A sharply resonant circuit is one that will not dissipate the energy of oscillations once started up in it at its natural frequency. A broad circuit has a high damping; it rapidly dissipates the stored-up energy. Similarly, if the state of the compound nucleus is one that tends to decay rapidly, its energy is poorly defined, Γ_i is large and the resonance is broad. If the compound level is narrow, the resonance is sharp.

Whether one should use the simple resonance ideas which involve a set of sharply separated levels, a modified resonance theory which takes into account many overlapping levels, with interference phenomena correlating the ways of formation and break-up, or the statistical method which assumes complete independence of processes, is a matter that depends upon the individual reaction under consideration. But within the limitations of our whole theory of the nucleus, we can feel satisfied that these various descriptions, each appropriate in a different domain, are consistent with one another, and block in a good picture of the rich and complex phenomena of nuclear reactions. They provide appropriate apparatus for understanding the varied excitation functions, from sharp resonances to constant cross sections, which we have already mentioned and will now discuss.

8. Some Typical Nuclear Reactions

We shall discuss these results from the two points of view already put forward: the dispersion theory and the statistical treatment. When low excitation energies and light nuclei are involved, the wave-lengths are not small compared with the nuclear dimensions, and the levels of the compound are more or less well defined; then we must use the ideas of resonance. For high energies and heavier nuclei, the specific quantum effects are not important; then the statistical theory is natural. The criterions will be, first of all, the level widths and level spacing for the reaction considered, and second, the possibility of coherence effects.

A. Resonance reactions

1. Slow neutron processes.—Nuclear reactions in which the incident particle is a neutron of very low energy have a special interest. However slow a neutron may be, it can still react with the nucleus, for the neutron has no charge, and hence experiences no forces but the centrifugal force, until it finally reaches the nuclear matter. Low energy charged particles, on the other hand, cannot reach the nuclear matter because of the presence of the Coulomb barrier and therefore do not react appreciably with the nucleus.

The neutrons released in some nuclear reactions, for example, the reaction $H^2(d, n)He^3$, have energies of several millions of electron volts. In passing through matter such neutrons are slowed down, not, of course, by ionization of the atoms they pass, as are charged particles which can interact with the electron shells, but only by collision with the nuclei themselves. Elastic collisions satisfy the conservation laws, discussed in Sec. 1. The energy given up by the neutron on impact, called the *energy of recoil*, is largest when the stopping particle has the same mass as the neutron. Thus neutrons lose energy most easily in passing through hydrogenous material, rich in protons. Paraffin or water is usually used for producing slow neutrons. The nuclei of the stopping material are not exactly at rest; because of their thermal motion they have kinetic energy $\frac{3}{2}kT$, where k is the Boltzmann constant and T is the absolute temperature. After very many collisions the neutrons will also have this energy. Such slow neutrons—at room temperature their average energy is approximately 1/30 ev—are called *thermal neutrons*. Most experiments on slow neutrons are conducted with these very low energy thermal neutrons.

A neutron of energy 1/30 ev—a common reactant—has a wave-length of approximately 10^{-10} cm; its collision with the nucleus is a purely wavelike phenomenon. Only the direct-hitting particles (represented by the s wave) will feel the nuclear forces. The p wave particles will not, on the average, come nearer to the nucleus than 10^{-10} cm, which is outside the range of the nuclear forces. Slow neutrons have negligible kinetic energy, so they excite the nucleus only by the amount of their binding energy, which varies around an average of about 8.5 Mev. With this excitation, and for A approximately 40, the slow neutron results show that there exist well-defined levels about $\frac{1}{5}$ ev wide, spaced by a dozen electron volts or so. As A decreases, both spacing and width increase, until for boron we have widths of some tens, and a spacing of several hundreds, of kilo-electron-volts. This is, of course, just what is expected from the model: lighter nuclei have fewer possible arrangements of the particles, hence fewer levels; and energy concentration is more likely, hence levels are wider.

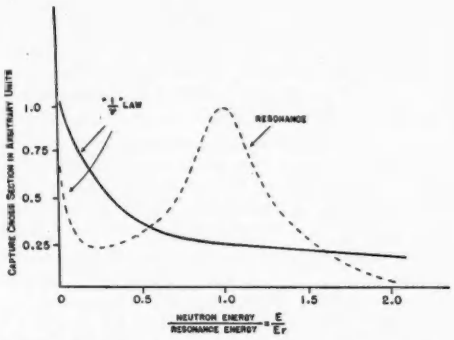

FIG. 5. Typical slow-neutron absorption cross sections. Note the $1/v$ law at low energies. The solid curve is like that for a light element, say, boron. The resonance level is so wide that its effect on the cross section is not noticeable. The compound nucleus disintegrates by releasing an α-particle, with a level width as great as 20 kev. The dashed curve shows a marked resonance, as in an element such as silver or rhodium. The resonance width is narrow because the competing reactions are radiation—always improbable—and re-emission of a neutron—a slow process because of the difficulty of energy concentration at low excitation energy in these heavier nuclei. Charged particles would, in addition, have to pass a high Coulomb barrier.

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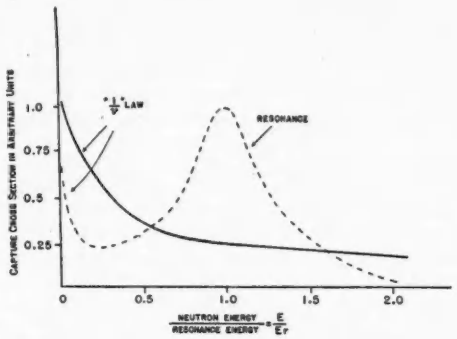

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slow over a few electron volts range in energy. The capture probability, given by Γ_n, depends on the detailed mechanism of capture and on the probability that a neutron will be within range of the nuclear forces. Over an energy range of a fraction of an electron volt the capture mechanism will hardly vary, while the probability that a neutron will be in the vicinity of the nuclear matter will be proportional to the time it spends in that region, or to $1/speed$ for each statistically independent state from which the neutron can be captured. The number of such states (which is proportional to the volume in phase-space they occupy) is proportional to the square of the neutron speed. The transmutation function must then contain the factor $1/v$, modified by the resonance level. If the resonance level is wide, its effect will be so smeared out that it will hardly affect the energy dependence of the cross section. This is the case with light elements such as boron and lithium. At sufficiently low energies the cross section is directly proportional to the contact time $1/v$. This is the "$1/v$ law" of slow-neutron absorption, which has been beautifully confirmed by experiment. (See Fig. 5.)

For light nuclei, the emission of γ-radiation, reduced by the factor 1/137 which measures the coupling between charges and the electromagnetic field, is improbable compared with the emission either of α-particles or of protons. For heavy nuclei the emission of charged particles is unlikely because of the large heat of evaporation over the Coulomb barrier. Thus for light nuclei we have slow-neutron induced reactions, such as $B^{10}(n, \alpha)Li^7$ and $N^{14}(n, p)C^{14}$; for heavier ones, $Cd(n, \gamma)Cd$ and $Rh(n, \gamma)Rh$.

2. Charged-particle reactions.—If the incident particle is charged, we must take into account the long distance interaction with the electrostatic field of the nucleus. Unless the energy is so high that, even after the particle has passed the repulsive Coulomb barrier, the wave-length of the incident particle is small compared with nuclear dimensions, we must apply the wave picture. The Coulomb barrier energy is just zZe^2/R, where z is the atomic number of the projectile and Z, that of the target. The nuclear radius R is approximately $r_0A^{\frac{1}{3}}$, since the volume is proportional to the number of particles. Then the barrier energy is approximately $0.5\ zZ$ Mev. For protons or α-particles, with energies of the order of magnitude of 10^2 kev for light nuclei, up to several million electron volts for the heaviest nuclei, the variation of the contact cross section with penetration factor, which we discussed in SEC. **6B**, will govern the transmutation function.

On this generally rising function of energy, which begins with a high order of contact at the threshold, and rises until the barrier height is exceeded and particle orbits begin to be well defined, is superimposed any effect of resonances. Resonance levels are relatively well marked for light nuclei; the ratio of width to spacing, Γ/d, is small; one or, at most, a few levels are involved. This fact means, of course, that predictions about the transmutation functions depend on the nature of the particular nuclear state involved. Because of the experimental ease with which homogeneous, well-collimated and steady beams of charged particles can be generated, quantitative tests of nuclear theory are most complete in this field—charged particle bombardment of light nuclei. The general features we already know: heavy-particle emission is faster than γ-radiation, once it is energetically possible; α-particles are less likely products as Z increases, and are common only among nuclei below neon. The Gamow factor[22] governs behavior at the threshold, and the transmutation rises rather rapidly from zero, with the contact probability. But the considerations coming from the specific states involved and the necessity for wave-mechanical description can be illustrated only by particular examples.

3. Selection rules: the reactions of lithium.—One of the most thoroughly studied[23] reactions is $Li^7(p, \alpha)\alpha$. Here the excitation function for energies up to 1 Mev follows the Gamow factor,[22] the contact probability, quite satisfactorily (Fig. 1); but it follows the course of the function with a centrifugal barrier, $l=1$. The direct-hitting particles of the s wave are not responsible for the bulk of the reaction. This can be understood by looking at the wave functions describing the system. The products are identical particles of zero spin, and hence the Bose statistics must be applied to them. This means formally that the interchange of the two α-particles must leave unchanged the wave function which describes them. Now, there is one constant of the motion in an atomic collision that has no simple mechanical analog. This is the so-called *parity*, a wholly quantum-mechanical idea which has been thoroughly tested in atomic spectra. It can be explained briefly as follows. A physical system must be the same whether we choose to describe it with reference to a right- or a left-handed set of coordinate axes. Therefore, chang-

[22] See *B2*, Eq. (631), and *B8*, p. 132.
[23] See footnote 7; also *B8*.

ing from a right- to a left-handed system, which is just the process of reflecting the system through the origin, must change the wave function, if at all, in a way that leads to no new physical results; the nucleus cannot know whether we are left- or right-handed. Since the physical properties of a system depend only on the absolute square of its wave function, changing the sign of the wave function will not change the described behavior. So reflection in the origin can either change the sign of the function, or leave it unchanged. Reflection can make no other difference. It turns out that we can classify all systems by their parity—by their behavior under this reflection. If the sign of the wave function changes, we say the system has *odd parity;* if it does not change, *even parity*. This parity is a "constant of the motion." It cannot be changed by any forces. If two particles have a relative orbital angular momentum l, and we reflect the system in the origin, the part of the wave function describing that motion has parity $(-1)^l$. If, in addition, the particles themselves are complex systems, they will have some parity of internal motion. Knowing this, we can calculate the parity of the whole system, which must be the same before and after the collision.

Any reasonable model of such a simple nucleus as Li^7—either the atomlike Hartree model or the model based on an α-particle structure—seems to give it odd parity. The proton is an elementary particle with even parity. Then the parity of the compound stage Li^7-proton initially must be $(-1)^{l+1}$, if the proton is taken into the stage with a relative orbital angular momentum l. But reflecting the product α-particles in the center of mass is the same as interchanging them, since they have equal masses and no spin. By the requirement of Bose statistics, the wave function must not change sign in this operation. Therefore the parity of the products must be *even*, and the incident proton must have had an *odd* orbital angular momentum. The most likely value of l is 1, since particles of higher angular momentum feel a higher centrifugal barrier. And, indeed, this fits the excitation function for this reaction and helps account for the relatively low yield, since the protons must penetrate a centrifugal barrier. But resonance is hardly apparent; the α-particle is easily emitted; Γ_α is large.

The distribution in angle of the resulting α-particles has been studied, and seems to be isotropic. This must be explained, making use of the conclusion we drew previously that the protons chiefly responsible had an angular momentum of one. Had only the s wave of incident particles been involved (as in all the slow-neutron reactions), this distribution would indeed have been necessary; for the s wave has zero angular momentum and this means that no direction in space is specified for the incident beam. Direct hits, the classical counterpart of the s wave, fix no axis of rotation. It is as though the incident particles of the s wave were equally likely to come in from any direction; then the angular distribution of the products must be isotropic, since no direction is defined in the experiment. For higher angular momentums, however, an axis of rotation is defined, and more complicated angular distributions must be expected. To find the possible angular momentums of the products of reaction, we need first to find those of the compound state, by combining the angular momentum of the incident particles and the spins of the reactants according to the rules of the spectroscopic vector model.

It is not possible here to say that spin and orbital angular momentums are each good constants of the motion, as in the atomic case where Russell-Saunders, or $L-S$, coupling is the rule. In nuclei we are sure only that the total angular momentum must be conserved. Study of the experiments alone will show how far we may apply the coupling schemes familiar in atomic work.

For the reaction $Li^7(p, \alpha)\alpha$, the orbital momentum of the protons, $l=1$, the proton spin, $\frac{1}{2}$, and the spin of Li^7, $\frac{3}{2}$, can combine to give a total angular momentum of 0, 1, 2 or 3, by the vector model. The compound state involved can have one of these possible total angular momentums. Since the initial wave had a more or less well-defined direction—with $l=1$— the isotropic distribution of the products means that the compound state had no "axis of rotation" at all, that it had total angular momentum equal to zero.

Consider next the reaction $Li^7(p, \gamma)Be^8$, in which the reactants are the same as before, but the products are different. This reaction shows (Fig. 1) a large yield at some 440 kev, which

comes from a very sharp resonance level, with a total width less than 11 kev. The cross section at optimum resonance, $\sigma_\gamma \cong \pi\lambda^2\Gamma_p\Gamma_\gamma/\Gamma^2$, and the fact that the total width Γ is approximately equal to Γ_p (since $\Gamma=\Gamma_p+\Gamma_\gamma$), give a radiative width of about 5 ev, again using the one-level dispersion formula. The level width is mostly the width from the proton capture itself. Radiation is typically slow. The disintegration of the compound state into two α-particles, as in the other reaction for these same reactants, would certainly go much more rapidly than radiation, if it were at all possible from this resonance level. It seems not to be allowed, even though there is energy enough. This suggests that the Be^8 compound level concerned has the wrong parity to break up into two α-particles, whose parity must be even. There is probably capture of s wave protons—giving a larger yield because there is no centrifugal barrier—and the compound level must have odd parity. Consequently, α-particles cannot be emitted. This explanation of the qualitative difference between the course of these two reactions from identical reactants is the most striking result of selection rules.

4. Other reactants.—A very interesting reaction is $F^{19}+p \rightarrow Ne^{20}$. Here, in this slightly heavier nucleus, are found not one but a dozen or more narrow resonances, spaced every 30 or 40 kev (Fig. 2). The levels of the compound nucleus, Ne^{20}, have become much denser, in accordance with our general picture. Beyond neon the levels soon become so dense that we can pass to the statistical picture.

In fluorine is observed[24] the reaction $F^{19}(p, e^+e^-\alpha)O^{16}$ at an energy of 5 Mev. This is the only known case where light particles are found in the reaction proper. It indicates a special character of the states involved, which are required to have zero angular momentum and opposite parity for the competing compound states, the one emitting γ-rays, the other an electron pair.

The competition $B''+p \rightarrow \begin{cases} 3\alpha \\ Be^8+\alpha \\ C^{12}+\gamma \end{cases}$ has been studied intensively.[25] Here detailed arguments have been made which parallel our discussion of lithium, but are necessarily more complex. In fact, it is still not possible to correlate the observed widths that govern the competition, the selection rules for angular momentum and the observed angular distribution.

Many experiments have been made with these light nuclei, where detailed tests of the theory can be made. The reactions with protons and α-particles as projectiles, and the targets H^2, Li, Be, B, C and N have been studied with special care. The somewhat unsatisfactory state of both the experimental data and the theoretical interpretation is shown by the fact that only the Li^7 reaction seems to be understood in all essential respects. There is much room for work on better transmutation functions, and especially on angular distributions, even in the low energy region. In any laboratory in which beams of charged particles of well-defined and controlled energies of a few hundred kilo-electron-volts, even if only small currents, can be obtained, careful quantitative work in this field is sure to be rewarding.

We have not spoken explicitly of α-induced reactions in this low energy, light nuclei domain. The α-particle is, to be sure, a complex system of four particles; but the binding energy is so large and the system so stable that, at energies below some tens of millions of electron volts, it behaves like an elementary particle. Thus our remarks about proton reactions apply to it quite well, except that one must take into account the energetics of α-particle reactions, and the fact that the Coulomb barrier for the α-particle is twice as high as that for the proton. The long wave-lengths of α-particles confronted with a high Coulomb barrier make the quantum-mechanical effects even more pronounced, and the resonance phenomena even more marked. Such nuclei as Mg^{24} and Al^{27} show fine resonances in (α, p) reactions. Because the first nuclear projectiles were the α-particles emitted from natural radioactive bodies, these are the classic examples of transmutation.[26] The marked resonance in these early cases may even have been responsible for the rather slow development of the many-body model of Bohr.

In general the reaction (α, proton) will be most frequent, because of the high "heat of evaporation" and reflection from the electrostatic barrier of the doubly charged α-particle which make it a

[24] Oppenheimer and Schwinger, Phys. Rev. **56**, 1066 (1939); Streib, Fowler and Lauritsen, Phys. Rev. **59**, 253 (1941).

[25] See *B14*; Hill and Haxby, Phys. Rev. **56**, 147 (1939); Jacobs and Whitson, Phys. Rev. **59**, 108A (1941).

[26] G. Gamow, reference 20, p. 206.

slow competitor. But the requirements of the wave picture make the sharp separation of this reaction into steps even more dangerous than in the case of low energy protons.

B. Reactions without marked resonance[27]

We have already described the theory of reactions in the statistical form suited to those cases where the spacing and width of the levels is such that we may expect a large number of the levels of the compound stage to be involved in every reaction. Of course, all the levels in a given energy range do not take part in every process. Constants of the motion which must be preserved in every stage of the collision will select out certain levels of the compound stage. The total angular momentum, for example, will usually have only a small number of possible values. So our statistical requirements are quite incisive; a large number of levels *of a suitable kind* must be available if our treatment is to succeed. This means that we must deal with nuclei considerably excited above the ground state, so that the rapid increase of levels with excitation energy has come into play, and with nuclei of a good many particles, so that the very complexity of the level scheme will make our statistical treatment a sensible one. At zero excitation, for nuclei with A about 100, the spacing of levels is about one for every half-million electron volts or so, as we know from γ-ray studies. At an excitation of some 8 Mev (from slow neutrons) the spacing is about one every couple of electron volts. And at 9 to 10 Mev there are about 50 levels per electron volt.

In employing charged projectiles, we must stay above 2 Mev for A larger than 50, so that the particles can penetrate the barrier. If the projectiles are neutrons, they must be fairly fast, with energy above 1 Mev, for then we can be reasonably sure of having dense, overlapping levels.

The statistical calculations can be applied to typical reaction types. In this range—heavier nuclei and relatively high energy—the specific reactants are not of much importance, except as they determine the charge of the target nucleus and the binding energy of the product particles. We can discuss reactions in terms of the projectile and the product particle. Many different examples exist for each such reaction type. Let us begin with neutron reactions.

(n, n). Having no barrier to climb, the neutron boils off more easily than other particles from a nucleus excited by neutron entrance. Thus, inelastic scattering is the more likely process for excitations above 1 Mev. Now Γ_n is surely greater than the radiation width; and it is also greater than the proton width, because of the proton's larger heat of evaporation, unless much more energy is available for the emission of the proton; that is, unless the proton binding energy is much less than 8 Mev. Usually, then, D_n is about unity, and the cross section for inelastic scattering of neutrons is simply πR^2. The energy distribution of the emitted neutrons is a Maxwell-like distribution.

$(n, 2n)$. If, after the (n, n) process has occurred, the residual nucleus still has enough excitation energy left to boil off another neutron, it will usually do so. It can also radiate the energy away, but unless there are less than 100 kev available, neutron emission is more likely. Then the cross section for the $(n, 2n)$ process is just that for the (n, n), but weighted by the energy distribution $I(\epsilon)d\epsilon$ of the outgoing neutrons in the two processes. It is simply

$$\sigma_{n,2n} = \pi R^2 \cdot \int_0^{\epsilon'} I(\epsilon)d\epsilon \Big/ \int_0^{\epsilon_{n\,\max}} I(\epsilon)d\epsilon,$$

$$\epsilon' = \epsilon_{n\,\max} - E_T,$$

where E_T is the threshold energy of the $(n, 2n)$ reaction, and ϵ' is then the maximum energy of outgoing neutron for which the residual nucleus can still emit another neutron.

(n, p). This reaction competes poorly with (n, n). It differs only because protons must penetrate the Coulomb barrier in order to leave the compound nucleus, and hence have a lower evaporation probability. The energy distribution of emitted protons can be plotted; the most striking feature is the fact that low energy protons are much less likely to emerge than low energy neutrons.

Charged-particle reactions.—(p, n). This is in general the most probable proton-induced reaction. Only near the threshold for neutron emission can (p, γ) and (p, p) compete with it,

[27] We follow *B9* closely.

because there more states of the final nucleus may be available for these other reactions. As Z increases, neutrons compete more and more favorably with protons, and D_n approaches unity. For $Z=30$ and a threshold of a few million electron volts, D_n is about $\frac{3}{4}$.

(p, p). If the energy is below the (p, n) threshold it will usually be sufficient for the emission of a proton, because the energy with which the proton is bound in the nucleus is lowered by the Coulomb repulsion. Then $\sigma_{p,p}$ will be just equal to the contact cross section. Above the (p, n) threshold, the (p, p) competition is slow at best.

For both of these proton reactions there is fair agreement between experiment and theory.

(α, p); (α, n); $(\alpha, 2n)$. All these may occur, with qualitative similarity to the proton reactions, but one must take into account the doubled height of the Coulomb barrier. The main difference is that the binding energy of an α-particle, which brings in four nuclear particles, is at least four times as inaccurately known.

(α, α). Because an α-particle does not evaporate easily, the process (α, α) is observed only in two extreme cases: with the lightest nuclei, where the Coulomb energy is unimportant; and with the heaviest nuclei, near the natural radioactive series, where the α-particle releases a very large amount of energy. On the basis of the formulas we have outlined, the cross sections are indeed very small.

Radiation.—The contact cross section for γ-radiation is formally like that for uncharged particles, since in both cases the intensity at the nucleus of the partial wave of a given angular momentum is the determining factor.

The higher the multipole order l, the larger is the angular momentum that can be carried off, and the less likely is the absorption. The "sticking probability" is now calculable, at least in part, since we have a theory of the interaction between the charges and the currents of the nucleus and the electromagnetic field. On this basis, one can calculate the absorption and emission probabilities for various modes of oscillation of the nuclear drop. The dipole[28] is always reduced by the charge and mass symmetry (SEC. 6D*3*), and quadrupole or even higher radiation types usually play a part. From the expression for σ_γ and the experimental value of $\sigma=10^{-28}$ cm^2 for γ-rays of 17 Mev, we get $\xi_\gamma \sim \epsilon/27\sigma$ Mev. The theory of radiation emission is rough in this statistical form but does not give misleading results.

For all these processes, experiment and theory, although not conclusive, agree quite well as far as they go. The cross sections for particle reactions have been calculated by setting ξ—the so-called "sticking probability"—equal to unity for the energies studied. To fit the experiment exactly, however, ξ would have to vary from about 0.3 to 1.3, even when the nuclear radius R, the only parameter at one's disposal, is chosen to minimize this variation. There is no obvious systematic tendency in the values of ξ needed. The agreement in order of magnitude and the randomness of the variation show that the statistical treatment of reactions is an excellent beginning for a thorough knowledge of detailed nuclear processes.

9. SPECIAL PROCESSES

A. Deuteron bombardment; the Oppenheimer-Phillips process[29]

We have so far avoided discussion of one of the most-used nuclear projectiles, the deuteron, ${}_1H^2$. Of the charged projectiles, the proton is an elementary particle, as far as we know today, while the deuteron and the α-particles certainly are complex structures, possessing states of internal motion besides the normal one of lowest internal energy. Nevertheless, the α-particle, like the proton, behaves in nuclear reactions effected at present-day energies as a simple particle showing no indication of internal motion; this great stability results from the fact that the binding energy is so large—more than 25 Mev—that the internal states are not excited at usual energies of reactions. In the deuteron, on the other hand, the energy binding the proton and neutron is only 2.17 Mev, which is considerably less than the kinetic energies available in modern high energy beams. One might therefore expect the loosely bound deuteron to show the effects of its internal structure.

This is the case for certain common deuteron reactions called *Oppenheimer-Phillips* reactions,

[28] Dipole radiation, which is proportional to the first moment of the charge density ρ (that is, to $\int \rho \mathbf{r} dV$, where $\mathbf{r}$ is the vector distance from the center of mass), is the "allowed" radiation in the atomic case, but for nuclei is reduced because the charge and mass are distributed fairly uniformly.

[29] See *B15* and *B16*.

after the authors who were the first to treat them theoretically. In an O-P reaction the deuteron is polarized by the nuclear electrostatic field; for the neutron does not experience any force until it strikes the nuclear matter, where it may be absorbed, whereas the proton is subject to the Coulomb repulsion and hence is kept away from the nuclear surface. Finally, the proton may break away from the neutron at the moment when the latter is absorbed and, moving down the potential hill, gain the kinetic energy with which it is emitted. O-P reactions, of which $Mg^{26}(d, p)Mg^{27}$, is an example, are most common for nuclei with $Z=30$ or more and for energies not too large compared with the barrier height. For light nuclei, or for very high energies, the Coulomb forces are not large enough to break up the deuteron; it acts then as a single particle, penetrating the Coulomb barrier in the usual way. Even in the lightest nuclei, however, the influence of the polarization cannot be neglected.

Actual calculation would involve a detailed knowledge of the wave function of the distorted incoming deuteron, and of the many-body interactions which take part. Just as with the simpler reactions, we can break the process up into several stages. Thus for a reaction initiated by a deuteron of energy W and resulting in the release of a proton with energy K in the energy range dK, the expression for the cross section must be written in the form $\sigma(K, W)dK=S(p_0)T(K)\xi dK$. Here $S(p_0)$ is the contact cross section for the penetration of the deuteron through the barrier to the distance p_0; p_0 is that proton position for which the penetration probability is a maximum; $T(K)$, which is called the *transfer factor*, takes into account the gain in energy of the proton from both (1) its recoil when the bond which holds it to the neutron is broken by the neutron's collision with the nuclear matter and (2) the Coulomb repulsion of the nucleus; ξ, the neutron sticking probability, is an average value obtained by taking into consideration the effects of all the nuclear levels into which the neutron may be captured; it becomes larger as the level density increases with the energy of excitation, and should be nearly unity for high excitation energy. If the neutron is captured into a state of very low excitation, this statistical average will not be adequate, because the effects of individual well-spaced levels will have to be considered. Cross sections are normal in size.

For a process in which the deuteron is not polarized, we have just $\sigma_i \sim S(R)\xi\Gamma_i/\Gamma$. Both proton and neutron reach the nuclear surface. At high energies, the most probable proton distance will not differ much from the nuclear radius, and the ordinary deuteron capture and the O-P reaction will have similar excitation functions. For $Z=30$, this energy will be about 5 Mev; for $Z=80$, 12 Mev.[30]

After entry of the neutron, the process proceeds as does any other reaction. The neutron capture may be followed by release of another neutron, by radiation or by other competitors, depending on the excitation energy. For the light nuclei the O-P reaction competes with capture of the deuteron, followed by boiling off a neutron, as in reactions such as

$$ {}_5B^{11}+{}_1H^2 \rightarrow \begin{cases} {}_6C^{12}+{}_0n^1 \\ {}_5B^{12}+{}_1H^1 \end{cases} . $$

B. Photo-disintegration; electronic excitation

The interaction of radiation with a nucleus is especially interesting because the γ-ray energy is quite sharply defined—γ-ray levels are narrow, thus affording the possibility of studying single levels—and because the electromagnetic properties of nuclei ought to be better understood than those properties that depend on specifically nuclear forces. For high γ-ray energies the level widths exceed their spacing (except in the lightest nuclei) and the cross section for photo-processes therefore should depend chiefly on the γ-ray energy. This seems to be the case, though the data are incomplete. The value of σ_γ is some 10^{-27} cm^2. Experiments with various γ-rays on many different targets will be useful in this study, if they can be made quantitative.

Reactions induced by γ-rays in very light nuclei, such as the photo-disintegration of the deuteron, will yield much information on the structure of nuclei and on the electromagnetic properties of nuclear matter; the chief need is for sources of strong γ-radiation of many energies. For heavy nuclei the drop model, in which the nucleus is treated as a rotating, vibrating drop of nearly uniformly charged matter, has yielded quantitative results that seem to be consistent with experiment.

Recently electrons of energy exceeding 1 Mev have been used to bombard Be and In. The reactions excited are $Be^9 \rightarrow Be^8+n$ and $In^{115} \rightarrow In^{115}+\gamma$. Presumably, the near approach of such electrons excites the nucleus, not by

[30] The proton energy distribution in a case where details of the compound levels are unimportant may be calculated; see *B16*, p. 874.

any specific nuclear-electronic interaction, but by the effect of the rapidly varying electromagnetic fields near the path of the fast electron.[31] Localization of the electron cannot be better than the distance $\hbar/mc$; and, of course, the wavelike, not the particle, picture must be applied. The effect is much like that of radiation.

C. Nuclear fission

In January, 1939, the most spectacular result in the whole field of nuclear reactions was announced—the famous *fission* of uranium. So far we have considered reactions of the type $T(i, p)R$, where both i and p are very light nuclei, ranging from proton to α-particle. But the fission of uranium involves the division of the nucleus into two nearly equal parts. A sample reaction is $U^{235}(n, Kr^{94})Br^{142}$. What is the explanation of this wholly new and unexpected result in which a huge nucleus, and not merely a proton or an α-particle, is "emitted" from the compound state?

The drop of charged matter constituting the nucleus of U^{235} is held together by the attractive nuclear forces, which act in the same manner as the surface tension and cohesive forces of a drop of water. Tending to blow the nuclear drop apart, however, is the Coulomb repulsion of the 92 positive charges in the drop, which nearly balances the attractive forces. The energy of this system is about 200 Mev larger than the total energy of the two nuclei $Kr^{94}+Br^{142}$, whose total charge and mass number are the same as those of $U^{235}+n$. The Coulomb forces have been reduced by dividing the drop and separating the charge. If the stable shape of the uranium drop is sufficiently distorted by vibration, the surface tension forces which hold the drop together are overbalanced by the Coulomb repulsion, and the drop divides into two roughly equal parts. Some excitation energy from the outside is required to distort the drop into its unstable form. The probability of the drop dividing spontaneously and the fragments tunneling through the deformation-energy potential barrier just as α-particles tunnel through the Coulomb barrier is, of course, not zero. But the fragments are so massive that, at the energies available, their wave-lengths are very small indeed compared to the barrier thickness, and the tunnel effect is very small. This "spontaneous fission" has, in fact, been reported, but with a lifetime of 10^{17} yr. It may be the reason for the termination of the periodic table of the natural elements with uranium; higher charge would make the drop unstable against spontaneous fission with a lifetime short compared with geologic times.

Let us sketch the calculation of fission probability.[32] The features of fission are essentially classical, because of the masses involved. When the incoming neutron strikes the uranium nucleus (neutron-induced fission is especially interesting, though proton-, deuteron-, and photo-fission are observable), its energy is distributed, with the effect of "heating" the nuclear drop. There ensues a competition between the ordinary processes of energy emission—radiation or release of a neutron—and the fission. When sufficient energy is concentrated into the mode of motion which corresponds to a distortion of the drop so marked that fission is possible, the drop divides. The treatment of the essentially classical fission problem has been patterned on the methods used to discuss chemical reactions in which an excitation or activation energy is required. In this method, we think of a potential surface where height at each point represents the energy of that configuration of the nuclear system which the other coordinates describe. These other coordinates are complicated; they include every variable needed to describe the shape of the drop—its ellipticity, necking-in at the plane of fission, and so on. Whatever they are, we think of finding the energy surface as a function of such variables. This surface must have a sort of crater at the peak, where the drop is in its nearly spherical, stable form. Some distance away from this crater is a deep valley, every point in which represents the system divided into two smaller nuclei. In between is a ridge, which represents the excitation energy needed to deform the drop away from its stable form. Across this ridge there will be passes—critical regions of unstable equilibrium. In order that the drop may divide, the point which represents the nuclear configuration must cross the ridge, and it can do this most easily through one of the passes. A narrow strip just athwart the crest of the pass will represent the critical state of the drop, called the *transition state*. Now consider the drop

[31] E. Guth, Phys. Rev. **55**, 411 (1939).

[32] Details will be found in *B18*, sec. III.

excited by the incident neutron. It is heated to some new temperature, with some energy of excitation. Then the points which represent the possible states of the nucleus will be distributed over the energy surface according to the usual Boltzmann distribution of kinetic energy, a function of the energy and of the number of levels available at each position. The points stream over the surface, reproducing the motion of the drop. Some chance to cross the pass, through the transition state; their relative number gives the probability of nuclear division.

Presumably, any of the isotopes above $A \sim 100$ could divide, for the energy is available. But only in the very highly charged isotopes, such as those of U, Th, Pa and perhaps a few others, is the balance between the nuclear cohesive forces —the "surface tension" of the drop—and the Coulomb repulsion so close that only moderate excitation energies are required to reach the pass in the energy mountain.

So far fission has been observed in U and Th. The pass in the U^{235} surface is so deep that slow neutrons will produce fission. This particular transition state involves the somewhat asymmetric deformation of the nucleus. The most common products of fission are the nuclei around $_{38}$Sn and $_{32}$Te, while almost no $_{47}$Ag or $_{46}$Pd is found in the products.[33] When fast neutrons with some 6 Mev of kinetic energy are used, another pass becomes accessible, and the fission products are distributed symmetrically around the most common product,[34] now $_{47}$Ag. The calculation of the positions of the passes as a function of the shape of the drop is carried out through quite classical treatments of the vibrations of a charged liquid drop. The results quoted seem to agree with the calculations.

When the drop fissures, the two nuclei which are formed are very much distorted from their normal states. They have many millions of electron volts of excitation. They appear to boil off several neutrons apiece, but, having done so, are still unstable compared with the normal isotopes of the same element because they have too many neutrons for their charge. Their typical behavior is to reduce to stable isotopes by a chain of high energy β-emissions, such as the observed chain,

$$\mathrm{Sb} \rightarrow \mathrm{Te} + e^- \rightarrow \mathrm{I} + 2e^- \rightarrow \mathrm{Xe} + 3e^-.$$

Radiation accompanies this process. The whole energy available for fission is thus released, largely as kinetic energy of the strongly repelled fragments, but also as β- and γ-radiation, and, very important, in the emission of several free neutrons.

The presence of these neutrons in the fission products gives the fission of U^{235} its technical promise. This nucleus will divide upon collision with a slow neutron. But after division not only is there a release of some 160 Mev—a very large energy for nuclear reactions—but some fast neutrons are produced. These will be slowed down in the matter of the target, and, unless captured first, will initiate another fission. For the first time we have the possibility of a self-sustaining reaction. For the first time a method is available that may yield not the few billion nuclear reactions of our strongest high energy beams but grams or kilograms of the dividing nuclei. The exciting possibility of nuclear power appears. Of course, the technical problems are very great; they are discussed in detail in the references.

Conclusion

It is appropriate to end our account of the theory of nuclear reactions with this approach to the threshold of nuclear power. The study of nuclei, apparently abstract, has not only led to a new understanding of the fundamental structure of the world but promises new control of that world, the control that always comes with understanding. Already experimental and theoretical progress in this field has led to rich results, of which the energy from fission is only the most spectacular. An understanding of the energy generation in stars, new possibilities in the radiotherapy of malignant diseases, a whole gamut of uses of radioactive tracer methods in chemistry, biology and geophysics—these are the by-products of nuclear research; and these results, with the impetus they will give to new technics and ideas, will in turn develop further our still incomplete, still growing understanding of the reactions between nuclei.

[33] For products, see *B19*, pp. 10, 23.
[34] T. Yasaki, Sci. Pap. Inst. Phys. Chem. Research **37**, 457 (1940).

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Experimental Examples in Dynamics

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IT has been my experience with students in dynamics to find that a good deal of the satisfaction of solving a problem is lost because there is no suitable demonstration to prove, even qualitatively, that the solution is correct. The difficulties in giving satisfactory demonstrations are divided between construction of the system and observation of the resulting motion. Usually the motion is too rapid to observe unless photographed. With the belief that others have had the same experience, I have taken four well-known problems in dynamics, constructed models and photographed their motion.

Diagrams of the systems constructed are shown.

In System 1 the motion of M_1 is given by the equation,

$$\frac{d^2x}{dt^2}=\frac{(M_3-M_4)^2g}{M_t(M_3+M_4)-(M_3-M_4)^2}, \qquad (1)$$

where g is the acceleration due to gravity, and

$$M_t=M_1+M_2+M_3+M_4.$$

From Eq. (1) we see that even though M_1 is balanced statically with $M_2+M_3+M_4$, it is not balanced dynamically because M_3 is not equal

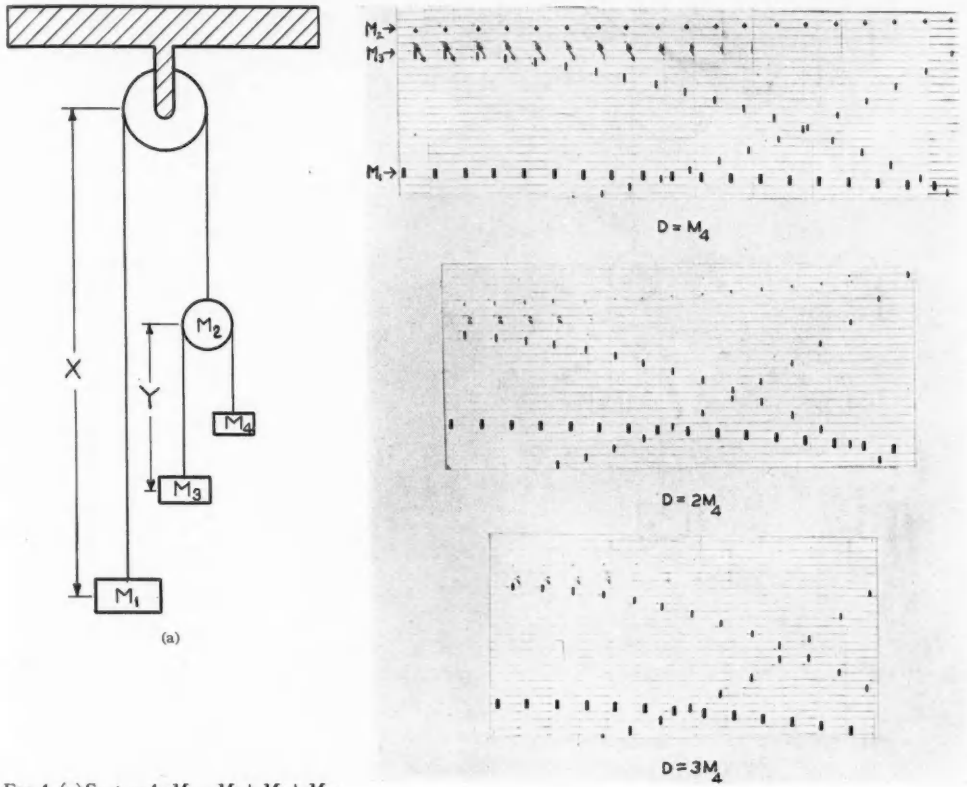


FIG. 1. (a) System 1: $M_1 = M_2 + M_3 + M_4$; $M_3 - M_4 = D > 1$. (b) Motions of System 1.

to M_4. Thus M_1 should fall; and as D, the difference between M_3 and M_4, increases, the speed of M_1 should increase.

These results, as photographed by a Sept camera taking 19 pictures per second at 1/70-sec exposure, are shown in Fig. 1(b) for the cases $D = M_4$, $2M_4$, $3M_4$. In Fig. 1(b) the large mass is M_1, the fixed pulley is not shown, and the distance between the parallel lines of the coordinate system is 10 cm.

In System 2 the motion of the pulleys is given by the equation,

$$\frac{d^2x}{dt^2} = \frac{(M_5 - M_6)^2 - (M_2 - M_3)^2 g}{M_t(M_5 + M_6) - (M_5 - M_6)^2 - (M_2 - M_3)^2}, \quad (2)$$

where $M_t = M_1 + M_2 \cdots + M_6$. Letting $D_1 = M_2 - M_3$ and $D_2 = M_5 - M_6$, we see that the two movable pulleys should remain side by side when $D_1 = D_2$. However, when $D_1 \neq D_2$ the pulleys should separate, and their speed of separation should increase as the difference between D_1 and D_2 increases.

These results, photographed with the same camera, are shown in Fig. 2(b) for the cases $D_1 - D_2 = 0$, $D_1 - D_2 = 2M_3 - M_6$, $D_1 - D_2 = 3M_3 - M_6$. The fixed pulleys and the masses M_3 and M_6 are not shown.

In System 3 we consider the problem of a rope over a pulley. To one end of the rope is fastened a mass M_1 and to the other end a mechanical monkey of mass M_2. The monkey pulls on the rope with a constant force equal to $M_2 a$. The equations of motion for this system are

$$\frac{d^2x}{dt^2} = \frac{(M_1 - M_2)g - M_2 a}{(M_1 + I/R^2)}, \qquad \frac{d^2y}{dt^2} = -a - [1 - M_1/M_2]g, \quad (3)$$

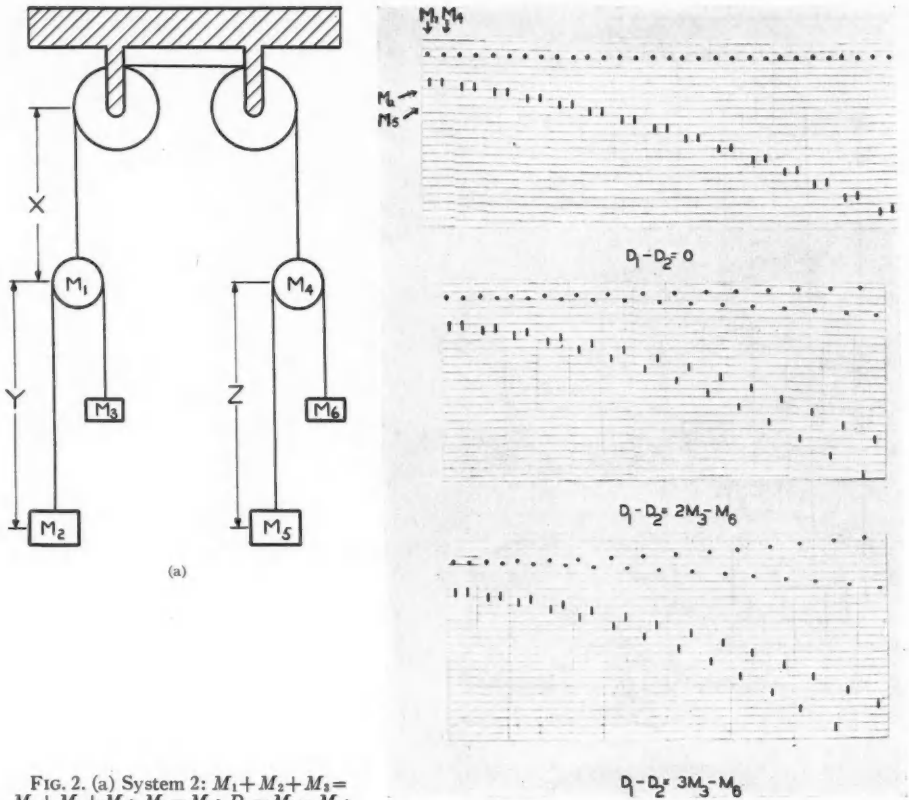


FIG. 2. (a) System 2: $M_1+M_2+M_3=M_4+M_5+M_6$; $M_1=M_4$; $D_1=M_3-M_2$; $D_2=M_5-M_6$. (b) Motions of System 2.

where I is the moment of inertia of the pulley, and R is its radius.

If $M_1=M_2$,

$$(d^2x/dt^2)=-M_1a/(M_1+I/R^2)$$

and

$$(d^2y/dt^2)=-a;$$

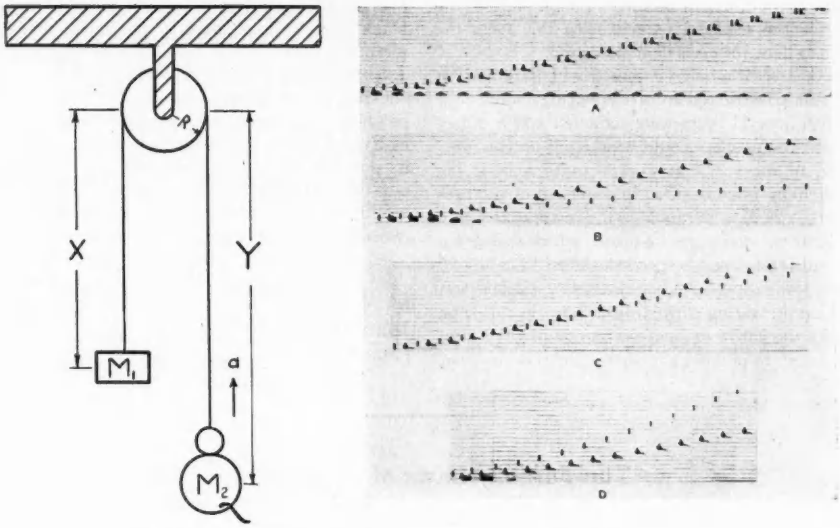
therefore M_1 should rise a little slower than the monkey (Fig. 3(b) *C*). If M_1 is made slightly less than M_2, so as to compensate for the moment of inertia of the pulley, then M_1 and M_2 should rise with the same acceleration (Fig. 3(b) *A*). If $M_1>M_2$, we have $|d^2x/dt^2|<a$, and $|d^2y/dt^2|>a$, both corresponding to motion upward; hence the monkey should rise more rapidly than M_1, as is verified in Fig. 3(b) *B*. If $M_1<M_2$, we have $|d^2x/dt^2|>a$, and $|d^2y/dt^2|<a$, both corresponding to motion upward; therefore M_1 should rise more rapidly than the monkey, as is shown in Fig. 3(b) *D*.

A very interesting demonstration is provided by System 4, which consists of a wooden pendulum, of length $R+L$, with a small brass ball resting on its free end. A small box is fastened at a distance L from the free end, L being chosen so that the final position of the box is directly below the initial position of the ball. The initial position of the top of the box is on a horizontal line with the bottom of the ball. The demonstration consists in allowing the pendulum to rotate to a horizontal position, with the result that the ball falls into the box.

When θ_0, the initial value of θ, is small enough so that $\sin\theta_0$ is approximately equal to θ_0, we find

$$t_1=(2R\theta_0/g)^{\frac{1}{2}},\quad t_2=(2(R+L)\theta_0/g)^{\frac{1}{2}},\qquad (4)$$

where t_1 and t_2 are the times for the box and ball,



(a) (b)

FIG. 3. (a) System 3: The climbing monkey. (b) Motions of System 3.

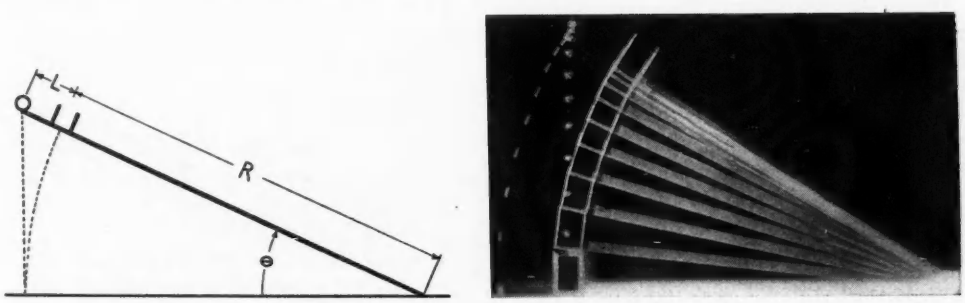
respectively, to fall. Thus $t_1 < t_2$ and the box should reach the horizontal position first so that the ball can fall into it. In an actual model, t_1 is smaller than indicated because the center of gravity of the pendulum is not at the center of the box but nearer the axis.

These results, as photographed with a stroboscopic camera taking 41 pictures per sec with an exposure of 3/5000 sec, are shown in Fig. 4(b).

To others interested in doing similar work, the following details should be of interest. The Sept camera, used for photographing Systems 1, 2 and 3, takes 35-mm single frame pictures and holds enough film for 250 exposures. For this work, the film used was Kodak Super—XX, and the lighting was supplied by three No. 2 photofloods and reflectors.

Before actually taking the pictures, it was necessary to release the systems without initial disturbance. This was done in System 1 by burning a thread joining M_3 to the movable pulley M_2; the burning match can be seen in some of the pictures of Fig. 1(*b*). In System 2 the release was accomplished as follows: one thread joined M_2 to the floor, and another thread joined M_2 and M_3 by way of the fixed pulleys; this second thread was then burned at a point between the fixed pulleys. In System 3, the monkey was released by hand.

The pictures were taken with a lens opening of *f*:5.6, and the negatives were developed in D-19 for 6 min. From these negatives, 1×7-in. enlargements were made on



a) (b)

FIG. 4. (a) System 4. (b) Motion of System 4.

paper of high contrast. The prints were then mounted side by side to give the required sequence. In this form the pictures are excellent for class demonstration.

In System 3, several monkeys were tried before a satisfactory one was constructed from the spring motor of a toy locomotive. Several gears were removed and a pulley inserted so that the monkey could wind itself up the rope. This monkey, of mass 227 g, worked quite well. If the pull of the monkey is constant, the sequence of pictures should show its rise as a parabola. This is approximately true, except near the end of the sequence where the spring is unwound and the monkey's speed slackens.

In photographing System 4, an Eastman Kodak was mounted behind a rotating slotted disk. Since in this type of photography the entire sequence is on one piece of film, care must be taken to prevent the separate exposures from overlapping excessively. Also, the background must be black, since it is exposed to the entire film each time a picture is taken. Thus, the ball was covered with tin foil and the free end of the pendulum was blackened so that the ball could be seen against it. The very tip of the pendulum was painted white so that its motion could be easily discerned. By using a black box outlined in white, its positions could be clearly seen, and yet it did not blot out the corresponding positions of the ball. The system was illuminated by three No. 2 photofloods, and the photographs were taken at *f*:4.5 on Ortho-Tri-X film.

It is a pleasure to thank Mr. Robert Kleinhenz for his assistance with the photography, and John Carroll University, where this work was begun, for its splendid cooperation.

The Faraday Laws of Electrolysis

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COMPARED with other laws in our general account of electricity, the laws of electrolysis seem simple. Certainly they are easier to understand than the laws of induced currents, and easier to apply than the Kirchhoff laws of the electric circuit. However, the laws of electrolysis have a significance beyond that specifically indicated in the conventional words. Concerning the charge of an ion, which he calls the "molecular charge," Maxwell[1] has said, "If it were known it would be the most natural unit of electricity." Also Johnston Stoney is quoted[2] as having said, in 1874, "it is almost a necessary consequence of the Faraday laws of electrolysis and of the atomic theory that electricity should be atomic in character. . . ." The reasoning seems to be that in the electrolysis of one substance the electricity transferred divided by the number of ions deposited gives actually the average charge, and the individual ions may be carrying different amounts. But this average charge comes out the same, insofar as numerical data serve to determine it, in the electrolysis of many different materials. It is simpler, therefore, to suppose that all ions have the same charge (or small integral multiples of it) than to suppose that ions of silver and ions of hydrogen manage to acquire and transport the same average charge, while the charges of individual hydrogen ions are different.

Moreover, if a consideration of the laws of electrolysis leads one to conclude that electricity is atomic, it leads also, when the Avogadro number is known, to a calculation of the atomic charge. In this respect the Faraday laws of electrolysis go beyond Ohm's law, Joule's law, the Coulomb laws and the Faraday laws of induction. For, while Ohm's law and the law for the heating effect of a current may follow from the electron theory of metallic conduction, they do not serve for any elementary calculation of the unit charge or of the Avogadro number. It is part of a clear and adequate presentation of the laws of electrolysis to bring out their atomic significance, and particularly to explain the connection between the electronic charge, the chemical and electrochemical equivalents, and the Avogadro number. Such a presentation is attempted in what follows.

It is possible to state the two laws in algebraic form, but it is not easy to deduce from the equations the atomic relationships just mentioned. It is more direct and impressive to deduce

[1] J. C. Maxwell, *A treatise on electricity and magnetism* (Oxford ed., 1873), vol. I, art. 260, p. 311.
[2] By G. E. M. Jauncey, *Modern physics* (Van Nostrand, 1935), p. 136.

the laws and their consequences and to compute the best value of the Avogadro number from a simple and obvious statement of the atomic situation.

Let the amount of material deposited on one electrode, of copper, for example, consist of N atoms, each of mass M/A. Here N is some number of the order of 10^{23}, M is the gram atomic mass, and A is the Avogadro number; M is determined by chemical means as a number relative to 16 for oxygen, and if, as usual, the substance has several isotopes, M/A is the average mass, considering all the atoms. Then the mass deposited is m grams and obviously

$$m=NM/A. \tag{1}$$

If a student is asked why this is true, we may discover that it is not obvious; but it is sufficiently obvious for the purpose of this paper.

An ion is an atom (or stable group of atoms) that, originally neutral, has become charged by the gain or loss of one or more electrons. The number of these electrons is v, the valence of the ion; hence, the charge of one ion is ve, e being the electronic charge. If the ions are positive they are deposited on the cathode, and each one acquires v electrons delivered by the current (since electrons move toward the cathode in the wire of the circuit outside the electrolytic cell). The result is that the cathode gains in mass by the mass of a neutral atom when one ion goes out of solution, though ion and atom differ a little in mass. Therefore N in Eq. (1) is also the number of ions deposited, and if Q is the quantity of electricity transferred across any section of the circuit while the mass m was being deposited, then

$$Q=Nve. \tag{2}$$

It may be added here that the supply of electrons for the current is furnished at the anode where negative ions give up their charges and make up a deposit of neutral atoms which may or may not accumulate on the electrode.

Equations (1) and (2) express our conception of the electrolytic process in outline. Elimination of N between them gives

$$m=(M/veA)Q. \tag{3}$$

This equation contains the two laws and more. For if different quantities of electricity pass through an electrolyte, so that different amounts of material are deposited, M and v are the same. Also e and A are universal constants. Accordingly, m is proportional to Q. This is the first law. Again, M/v is the chemical equivalent of the material deposited; and if the same quantity of electricity passes through several cells, different masses of different materials are deposited. Since Q is the same for all, and e and A are constants, the different masses—expressed by m in Eq. (3)—are proportional to the corresponding chemical equivalents. This is the second law.

Equation (3) is valuable not only as a single statement of the two laws but also in their interpretation. If the first law is written in the form

$$m=zQ, \tag{4}$$

z is by definition the electrochemical equivalent. Then according to Eq. (3),

$$z=M/veA. \tag{5}$$

If the chemical equivalent M/v is c,

$$z=c/eA, \quad \text{or} \quad A=c/ze. \tag{6}$$

This gives the relationship demanded at the beginning. Using the values for silver, since they are commonly and precisely known, we have

$$A=107.88/0.0011180\times1.601\times10^{-19}$$
$$=6.027\times10^{23} \text{ atoms per gram atom.}$$

This is also the number of molecules in one gram molecular weight. The 7 is uncertain, since we are not justified in writing more digits in the value of e. But this is a satisfactory method of finding the Avogadro number, which plays so large a part in the arithmetic of physics, for example, in calculations of the atomic spacing in crystals and in the kinetic theory of gases.

Equation (6) enables us to write $eA=c/z$ $=107.88/0.0011180=96{,}494$, with some uncertainty in the last digit. The significance of this number appears if $m=c$, that is, if the mass deposited equals the chemical equivalent. Then, from Eq. (3), $Q=eA$. Therefore 96,494 coulombs must be sent across any section of the circuit in order to deposit one chemical equivalent of any substance that is capable of being deposited by electrolysis and has a definite chemical equivalent. Accordingly, 96,494 is the number of coulombs per chemical equivalent deposited.

We could also write $z=c/96{,}494$, or, if convenient, $m=cQ/96{,}494$.

Beginning again with Eq. (4) we may write the first law for a single atom as $M/A=zve$, giving $z=M/veA$, which is Eq. (5). This is another way to derive the complete equation, and it is even simpler. But we have accepted the first law as empirical, and the first method seems more unified.

Since fairly accurate values of the Avogadro number were at hand for many years before physicists determined the charge of the electron, it would have been possible to calculate the average charge of a monovalent ion by reversing the process used here for A. Perhaps that was done, but people were not impressed by the significance of the result.

If one looks through the textbooks of general physics he will find the laws of electrolysis attributed to Faraday, but stated in a great variety of ways. Perhaps the variety is due to the fact that Faraday did not state explicitly what we call his laws. At any rate, I do not find them in his *Experimental researches in electricity*.[3] Perhaps that is not to be expected. In paragraphs 377, 783 and 821 of the *Researches*, Faraday gives "the important proposition . . . *that the chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes.*" And in paragraph 839 he says, about certain substances, that "*their electro-chemical equivalents* are the same as their *ordinary chemical equivalents.*" Naturally, Faraday did not express electrochemical equivalents in terms of the coulomb, but determined the chemical equivalent by electrical means. He says of water, in article 732, "*where subjected to the influence of the electric current, a quantity of it is decomposed exactly proportional to the quantity of electricity that has passed . . .*," and he proceeded to use the mass of water decomposed or of hydrogen evolved as the measure of Q. The instrument designed and constructed for this purpose (Article 839) Faraday called a volta-electrometer.

[3] M. Faraday, *Experimental researches in electricity* (1839), vol. I, art. 839 and others. They are not in the sections reprinted in *A source book in physics* by W. F. Magie, nor in the articles in the Harper memoir, *The fundamental laws of electrolytic conduction*, by H. M. Goodwin.

A Two-Dimensional Kinetic Theory Model

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ALTHOUGH the kinetic theory, at least in its elementary aspects, is so beautifully simple that almost anyone can visualize its explanations, everyone whose teaching in any way involves this theory has felt a need for an actual demonstration model with which to illustrate it. Such a model serves to enliven the discussion and to assist the beginner in grasping and retaining the explanations; moreover, even those best versed in the theory enjoy viewing the demonstrations and often may see new significances in their repetition. Various models have been described,[1,2] and doubtless many others have been devised. Only one such model is now to be found in the catalogs of physical apparatus; in this one, which was designed by Stoekle, molecules are represented by glass beads, maintained in a state of continuous agitation by an ascending column of mercury vapor. It illustrates beautifully the random motions of molecules, but this is the limit of its usefulness.

The apparatus to be described here has been designed and built by the author to meet his need for an inexpensive kinetic theory model that will illustrate as many as possible of the phenomena which are accounted for by the kinetic theory. A two-dimensional model seemed preferable, not only because it is simpler to construct, but also because the molecule-like motions are easier to follow with the eye when confined to a plane. Ping-pong balls are used as "molecules." As many other model builders have discovered, these balls serve this purpose excellently and make possible a model large enough to be seen directly by a large audience. The vertical chamber in which the balls are

[1] Sutton, *Demonstration experiments in physics*, pp. 459 ff.
[2] L. de St. Paer, Sch. Sci. Rev. **21**, 1010–1013 (1940).

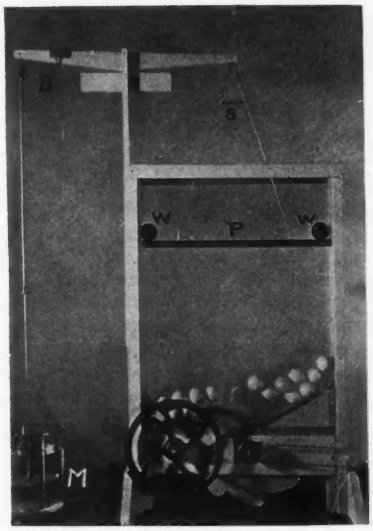

FIG. 1. Kinetic theory model.

confined is formed by two glass plates, 18 in. wide and 24 in. high, separated only far enough to allow free motion of the balls between them. A simple rotating agitator, working through a slot in the bottom of this chamber, maintains the motions of the balls (Fig. 1). Various auxiliary pieces of apparatus may be introduced at the top of the chamber to make possible the demonstrations described below.

DEMONSTRATIONS

1. Random motions of molecules.—When the agitator is rotated quite slowly the ping-pong balls roll and tumble about in a manner that probably well simulates the motions of molecules in a liquid. Those at the surface bounce up and down, and occasionally one or more will leave the surface for a flight into the space above, sometimes with quite high speed. This, of course, graphically illustrates surface evaporation. When the agitator turns more rapidly, all the balls fly about with random motions, colliding with one another and with the walls, and the gas state is realized. The appearance of their motion is now very striking. With 15 balls in the chamber the mean free path is about 8 in.; collisions between balls are thus frequent enough to insure a quite random distribution of motion, both as to direction and speed. Variations in speed, as well as in direction of motion, may be seen quite easily. Statistical variations in "density" are likewise apparent; they are very noticeable in the photographs of Fig. 2. These fluctuations from average values are of especial interest to advanced students; although students may be persuaded of the existence of such fluctuations by what they read in their textbooks, they are much more convinced after seeing the actual occurrence of fluctuations in this model.

In addition to such random variations of density there appears a vertical variation of density due to gravity which illustrates, on a small scale, the dependence of atmospheric density upon elevation. Under typical conditions of operation the density varies in the ratio of about 3 to 2 from top to bottom of the chamber. This corresponds to a difference in elevation, in air, of about 3 km.

2. Gas pressure.—The arrangement of apparatus for this demonstration is shown in Fig. 1. The piston *P* is a strip of wood which fits loosely between the walls of the chamber; it hangs from one end of a simple beam and is balanced by counterweights hung from the other end of the

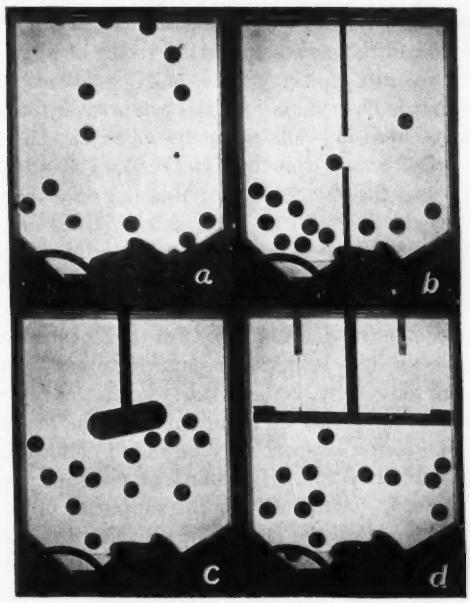

FIG. 2. Several applications.

beam. The bouncing balls drive the piston upward with an *average* force which may be balanced by the weights placed in the scale-pan *S*. Since the instantaneous force on the piston varies considerably from this average, the piston tends to oscillate irregularly (a type of Brownian motion) unless the motion is damped by means of a metal disk *M*, suspended in a dish of water to form a dash-pot. Friction between the glass walls and the piston is made negligible by means of metal buttons (thumbtack heads) which project slightly above the side surfaces of the piston, one at either end of each side. Greater care must be exercised to avoid friction at the ends of the piston; two small wheels *W*, taken from a 10-cent toy, "lubricate" it at these points.

"Pressure," in this two-dimensional case, is the force *per unit length* of the piston. Its maximum allowable value is set by the endurance of the ping-pong balls. With 15 balls, forces up to 40 g (pressure of 1 g/cm) may be reached without excessive breakage. The laws of statistical variations guarantee that an occasional ball will suffer a collision too violent for its internal structure; the best one can do is to keep the breakage within reason. When a ball does break, an obvious analog to chemical dissociation may be pointed out. With the piston at about the middle of the chamber, and a pressure of 1 g/cm, the average speed of the balls is about 250 cm/sec. The value of the temperature thus represented depends upon the value chosen for the Boltzmann constant k. For $k=1.38\times10^{-16}$ erg/deg, the value which applies not only to gas molecules but also to Brownian particles of all kinds, the temperature is of the order of magnitude of 10^{20} °C. *This is the temperature needed to maintain such a motion thermally* (by true molecular bombardment). For demonstration purposes it is better to assume a much larger value for k—say, 200 erg/deg—so that ordinary temperatures may be represented by the model.

The piston support may be raised or lowered to enable one to study change of pressure with volume. Unfortunately for the simplicity of this demonstration, the change of pressure does not at all follow Boyle's law, as Table I shows; consequently the results may be considered only qualitatively in elementary classes.

TABLE I. *Relation of P and V.*

V (cm²)	P (dyne/cm)	PV
8.1×10^3	13.0×10^3	105×10^4
11.7	7.0	82
16.2	3.7	60
21.6	2.2	48

In accounting for this "failure" of Boyle's law, consideration must be given first to the variation of pressure and density with elevation, due to gravity; the computation of numerical values for this variation forms an excellent problem for more advanced students. In the second place, it is quite probable that the effective "temperature" increases as the volume is decreased even though the speed of the agitator remains constant. Indeed, it is incorrect at any time to consider the effective temperature as uniform throughout the chamber; since the balls lose some energy at every collision their average speed must decrease with distance away from the agitator. This condition, in the ping-pong ball gas, is somewhat analogous to that of a real gas in a container which is heated at one wall only and loses heat by conduction through the other walls. Since, in the ping-pong ball gas, energy disappears throughout the volume as well as at the walls of the container, another analog might be the losses by radiation which occur in a real gas when it is at a sufficiently elevated tempeature. All these factors are susceptible to mathematical computation, the results of which may be checked against experimental observations. Such studies are now under way in our laboratory.

3. Diffusion through a porous plug.—As shown by Fig. 2*b*, the "porous plug" consists of a vertical partition broken at its mid-point by a 2-in. gap, the two parts being held together by thin celluloid strips which lie close to the glass walls. If one side of the chamber is now "cooled to absolute zero" by placing a horizontal partition across it just above the agitator, and all the balls are placed initially in the other side, the process of diffusion may be observed in its simplest form. Whenever a ball "collides" with the "pore" it passes into the other side and there "condenses." This one-way diffusion process takes place slowly enough to be followed very easily. Quantitative observations show surprising variations. If, for example, an attempt is made to show how the rate of diffusion depends upon temperature (speed of the agitator), it will be discovered that random variations of this rate completely mask the variations of rate with speed unless averages of many observations are taken.

Such statistical variations, which represent

one of the most interesting aspects of this apparatus, are even better shown when both sides of the chamber are made similar by removal of the horizontal partition, conditions then being as shown by Fig. 2*b*, and equal numbers of balls are placed initially in both sides. If now the apparatus is stopped at successive equal intervals of time and the balls counted, considerable variation from the average will be observed; at one time the author was so fortunate as to observe *all* the balls on one side! The distribution curve for many such observations may be used to demonstrate the theoretical laws for such statistical variations. The mixing of two gases by diffusion may be demonstrated by putting white balls on one side and an equal number of colored balls on the other side.

4. Brownian movements.—This is perhaps the most striking and most valuable demonstration, since the mechanism of the Brownian motion, which is not always apparent from lecture or textbook discussions, is clearly apparent here. A wooden disk, about 1 in. thick and 4 in. in diameter, represents the smoke particle of the usual Brownian movement experiment. The simplest support for this Brownian "particle" is a spring attached to the top of the chamber, of such a length that the disk hangs near the middle of the chamber. The very lively motion of the disk which results from the ping-pong ball bombardment is a quite satisfactory demonstration for elementary courses. A closer analog to the Brownian movements as usually observed is obtained by suspending the disk as the bob of a fairly long pendulum, from a point some distance above the top of the chamber. The pendulum cord passes through a slot in the cover. Since this slot can be made narrow enough to prevent escape of the balls, the cover is still "airtight" to the ping-pong ball gas! The movements then seen are practically horizontal and include both the erratic short distance motions and the longer distance wanderings characteristic of the Brownian motions usually observed.

5. Brownian rotations.—Figure 2*c*, shows an elongated "Brownian particle" pivoted freely at its center. It is supported from the cover by thin brass strips which lie close to the glass walls so as not to impede the motions of the balls around the particle. Under bombardment by the agitated ping-pong balls the motion of this pivoted body varies from slight oscillations to fairly prolonged end-over-end rotations. This demonstration is the large-scale counterpart of the beautiful experiment[3] in which flat crystals of lead carbonate serve as Brownian particles.

6. Molecular rotations.—The pivoted wood block described in *Sec. 5* may also be considered to represent a large rotating molecule; but a "diatomic" model, made from two ping-pong balls, shows much livelier motions. The two balls are joined by a rubber band, threaded through holes drilled along their diameters and knotted at its ends; the little dumbbell thus formed spins upon an axis consisting of a piece of stiff wire passed between the balls and through the rubber strands.[4]

7. Brownian motions of a tuned system.—When a mechanical system which is capable of free vibrations is subjected to the bombardment of the ping-pong ball gas its erratic motion will be a Brownian motion of vibration. This type of Brownian motion is illustrated by the wood disk suspended from a spring, as has been mentioned in *Sec. 4*. It is likewise characteristic of the motion of the piston described in *Sec. 2*. This phenomenon, which has no counterpart among the Brownian movements usually observed, is excellent for quantitative study. Figure 2*d* shows a suitable form of apparatus. A fairly heavy bar is pivoted at its center and held by two springs so that its position is horizontal across the middle of the chamber when it is at rest. It is long enough to confine the balls to the space below it; in other words, it is an oscillating piston. When the balls are at rest, "condensed" at the bottom of the chamber, this bar may oscillate quite freely with fairly small damping. When the balls are in motion the situation is quite different. The bombarding balls will quickly damp down any large oscillation (an exact analog to air damping); they will not, however, bring the bar to rest but will maintain it in a state of irregular oscillation whose *average* kinetic energy, like that of any Brownian particle, equals the average kinetic energy of the

[3] Reference 1, Exp. A-50, p. 463.

[4] The author is indebted to R. E. Gibson, who suggested this demonstration and method of construction.

ping-pong ball "molecules." In addition, of course, there is an equal average amount of potential energy. The significance of this, when the vibrating bodies are diatomic molecules, should be pointed out to students.

Other applications of this apparatus may occur to users of it. A systematic investigation of its quantitative possibilities is now being undertaken by one of our students, Harold Argo.

Constructional Details

The primary problem in the design of any kinetic theory model is that of obtaining an effective yet simple agitator for the particles which represent the molecules. It is principally in this respect that the various models differ from one another. Since ping-pong balls, unlike the molecules which they represent, are not perfectly elastic, some means must be provided to supply the energy lost in collisions among themselves and with the walls of the chamber. In the present model (Fig. 1) the agitator is a rotating cam-wheel, $\frac{3}{4}$ in. thick and 11 in. outside diameter, having eight lobes whose driving faces are roughly segments of logarithmic spirals. Its corners are rounded to a curve equal to that of a ball; if any sharp corners exist within the chamber, balls will be broken very frequently. Since the agitator must drive the balls always upward, its axis is placed below the chamber, with the upper part of the cam-wheel projecting into the chamber through a slot in its bottom. The use of a slotted bottom, "airtight" to the ping-pong ball gas, is a distinctive feature of this design. The impulses given the balls by the agitator are not radial, but perpendicular to the cam faces; hence the agitator axis must be displaced about 1.5 in. to the right of the center line of the apparatus in order to distribute the impulses uniformly. The bottom walls form a sort of hopper which limits the impulses to upward directions between the limits of 60° to either side of the vertical; they must be carefully located, so as never to make an angle less than 90° with the cam faces, or the balls may be pinched and excessive breakage result.

The agitator may be rotated by means of the hand drive wheel, or by an electric motor; the latter is necessary for quantitative work. The hand drive makes the apparatus self-contained; this is an important advantage, since the apparatus is in demand for chemistry, botany and zoology classes as well as for both elementary and advanced physics classes.

It is important that the glass walls of the chamber be separated only far enough to allow free motion of the balls between them. When a spacing of 2.5 in. was tried the motions of the balls, which are 1.5 in. in diameter, exhibited a viscosity-like phenomenon of considerable magnitude. This behavior is easily explained: Oblique collisions between the balls drove them against the glass walls with considerable force, and upon rebound they traveled but a short distance before striking the opposite wall; thus they rebounded back and forth between the walls repeatedly until much of their energy was dissipated. When the chamber thickness is made 1.75 in., all collisions take place practically in the one plane and this phenomenon is not noticeable.

Obviously it is possible to make a three-dimensional model by placing a gang of such cam-wheels upon a common shaft in a deep chamber. Slats properly placed between the cam-wheels would form the bottom of this chamber. The difficulties of construction would be increased, not only for this detail but also for many of the accesories, and no great advantage would result. Indeed, the two-dimensional model appears preferable. In addition to the advantages which have been mentioned elsewhere in this paper there should be added the very satisfactory photographs, both "stills" and "slow-motion" movies, which may be taken when all the molecules lie in one plane. The slow-motion movies are exceptionally interesting.

Two-Dimensional Gas Theory

The modifications which must be made in the usual kinetic theory to make it applicable to a two-dimensional gas are fairly obvious, and the resultant equations differ from the familiar ones only in the constant factors. For example, the gas equation and the expression for the mean free path l become, respectively, $PV=\frac{1}{2}mNU^2=NkT$ and $l=1/4Rn$, where N is the total number of particles and n, the number per unit "volume"; m is the mass of a particle and R, its radius; and U is the root-mean-square speed. The necessity for making such modifications is often of real advantage in driving home to the student the fundamental concepts of the kinetic theory.

Demonstration Experiments

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IN reviewing *Demonstration experiments in physics*[1] I said:[2] "It is to be hoped that the publication of this collection of experiments will bring to light many others, now generally unknown, which for any reason serve their purpose better than those here described." In that spirit, I venture to suggest changes in, or substitutes for, some of the experiments there given and to describe a few others, which, though not new, may be of interest to some who do not now know about them. Reference to subject matter in the afore-mentioned book will be made by the letter and number designation there used.

Air resistance and free fall of bodies (M-79)

The classical experiment in which a coin and a feather are dropped together in a long glass tube which may be exhausted of air, can be replaced to advantage by the following procedure because of greater simplicity and better visibility. The lecturer, preferably while standing on a chair, drops simultaneously a metal sphere and a sheet of paper about 8 in. square. The paper, of course, flutters to the floor some time after the ball has reached it. The paper is next wadded into a compact sphere to reduce air resistance and the two bodies on falling now reach the floor at practically the same time. Yet, a recent textbook states that in falling even a short distance a large lead ball and a cork ball of the same size "would not fall in the same time at all."

Change of atmospheric pressure with height (M-325)

The following form of apparatus is believed to be much better than the one described. Two tubes *A* and *B* (Fig. 1) of internal diameter about 12 mm are supported in stands side by side with their ends at the same level. Rubber tubes *CC*, 40 cm long, connect *A* and *B* through *D* and *E* to the gas cock, which is adjusted so that the flames *L* and *H* are about 2 cm high. If *B* is now raised only 2 or 3 cm, the flame *H* will become markedly longer than *L*. Owing to the large size of the openings and the small height of the flames, the excess pressure inside the tubes is so slight that a small change in elevation in *B* produces an astonishingly large effect on the relative heights of the two flames. In this arrangement both flames are clearly visible for one position of the eyes, and this juxtaposition of the flames makes a more accurate estimate of their relative heights possible than in the method given in the book. Naturally, what the experiment shows is that the atmospheric pressure decreases more rapidly with elevation than does that of the less dense gas inside the tube.

Growth of crystals

This beautiful and instructive experiment is performed with a polarizing apparatus, such as L-136, in which Polaroids may replace the Nicol prisms. To prepare the necessary slide, which by the way will last several years, a piece of doubly refracting crystal of a substance, such as benzophenone, which has a low melting point

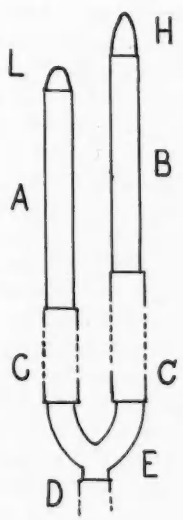

FIG. 1. Change of atmospheric pressure with height.

[1] *Demonstration experiments in physics*, edited by R. M. Sutton (McGraw-Hill, 1938).
[2] J. Zeleny, Rev. Sci. Inst. **10**, 111 (1939).

is placed on a piece of glass about the size of a large microscope slide and warmed until it has melted. A cover glass is now put on the melted drop and pressed down gently so as to leave only a thin layer of liquid underneath. If the liquid does not solidify on cooling, it may be made to do so by placing a small piece of crystal at the edge of the cover glass. To carry out the

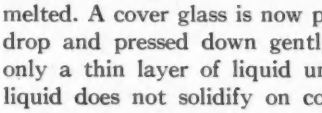

FIG. 2. Effect of temperature on viscosity.

experiment, the slide is first heated gently until the substance is almost but not quite all melted, and then is placed between the polarizer and the analyzer and projected on the screen. As the slide cools, the crystals, showing brilliant colors, begin to grow into the liquid which forms a dark background on the screen. The growth is often more rapid outward than sidewise, showing that the molecules attach themselves more readily to some faces than to others; but the crystal angles remain unchanged.

Complex transverse vibrations of a string

The vibrations of a string may be effectively shown by projecting onto a screen, by means of a set of rotating lenses, a small portion of a horizontally stretched piano wire about 1.2 m long and 0.5 mm in diameter. A sheet of metal having in it a vertical slot about 2 mm wide is placed close to the wire, and the light of the lantern is concentrated onto this slot where the wire crosses it. The image of this slot cast upon the screen by the rotating lens forms a continuous band on which the dark piece of wire describes a complex periodic curve whose components may be changed by plucking the string at different places.

A suitable set of rotating lenses consists of 4 lenses of diameter 2 in. and focal length 4.5 in. which are mounted on a circular disk with centers 4.5 in. from the axis of rotation. The vertical rotating table may be operated by hand or by a small motor with a variable resistance in series. At the proper speed the patterns formed by the successive lenses overlap to give a stationary picture.

Doppler effect in sound (S-150)

I have always found that a considerable number of students are so deficient in training in the perception of differences in pitch as to be unable to recognize the differences occurring when a sounding source is moving rapidly in a circle. The simultaneous changes in intensity in this case also cause some confusion. However, all are able to hear the beats produced, by the superposition of the direct and reflected wave systems, when a broad-pronged heavy fork of frequency 2048 vib/sec is moved near a wall of the room toward and away from the class. Unless the fork is moved quite slowly the beats are too rapid, and it is well to begin by holding the fork stationary for a moment in order that the students may first get the "feel" of the normal sound. I believe that the heavy forks mounted on a wooden handle which are made for showing the Doppler effect are supposed to be used in this way rather than for the direct observation of changes in pitch when the fork is moved rapidly.

Effect of temperature on viscosity of liquids (M-57)

A simple way of showing the large decrease in the viscosity of a liquid when its temperature is increased from cold to hot is to let water run from a vessel *A* (Fig. 2) through a tube *B* of length 1 m and diameter 1.5 to 2 mm. The end of the tube may be projected on the screen. The inclination of the tube *B* is gradually changed until ice cold water just issues from its end in drops. When hot water is now poured into *A* to replace the cold it runs out in a continuous stream.

Liquefaction of air at atmospheric pressure (H-109)

When liquid air still rich in nitrogen is used in the test tube connected to the vacuum pump, we find it is quite unnecessary to surround this tube with another tube that has been precooled. Some frost naturally forms on the tube but this does not interfere with the liquid air falling in drops from the bottom of the tube. The added simplicity makes the experiment more impressive. The identity in principle of this experiment and the condensation of water vapor on a dew point hygrometer is evident.

Dissectible Leyden jar (E-64)

I question the statement that this experiment shows that the energy of the charge resides in the dielectric. When the jar is charged, the opposite charges spread from the loose fitting coatings onto the glass where they are nearer to each other, and hence when the coatings are removed the charges in large part remain behind on the glass. If the charges had not spread to the glass the latter would not remain polarized very long after the metal parts are removed.

Iron nonmagnetic at high temperature (E-104)

A more simple way of showing this effect than that given is the following. A bar magnet *A* (Fig. 3) is supported above the table in a horizontal position and a strip of soft iron *B*, with a short bend at its end, is placed on top so that it extends a few centimeters beyond the magnet. Finally, an iron wire *C*, about 35 cm long and 0.7 mm in diameter and carrying an index *D*, is suspended magnetically from the end of *B*. The place of contact between *B* and *C* is now heated with a burner and, as soon as the wire gets red hot, it loses its hold and slips

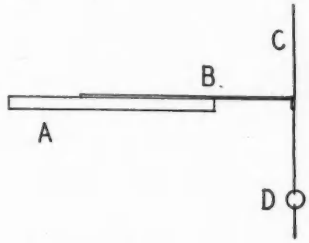

FIG. 3. Iron nonmagnetic at high temperature.

down, only to be held again when a colder portion of the wire reaches *B*. Continued heating causes the wire to descend by steps.

It is now believed that this critical temperature is not directly connected with the change in crystal form at which recalescence occurs. The two points are usually close together, but this is not necessarily the case.

Recalescence in iron

The form of apparatus for heat expansion merely mentioned under **H-10** serves so admirably for showing the point of recalescence also that it deserves a description in order that it may be copied with confidence. The iron wire

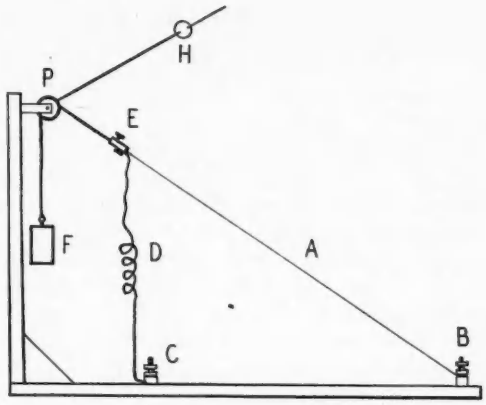

FIG. 4. Recalescence in iron.

A in Fig. 4, about 80 cm long and 0.5 mm in diameter, has its ends fastened to the binding posts *E* and *B*. Also fastened to *E* are a copper wire *D* that leads to the binding post *C*, and a string that passes over the pulley *P* to the weight *F*. The pulley *P* is 1.5 cm in diameter and carries an indexed pointer *H*, about 20 cm long. A current is passed through the wire until it is red hot. After the current is interrupted the pointer gradually descends, only to rise again momentarily when the point of recalescence is reached.

Peltier effect (E-180)

The most novel thing about the Peltier effect is the cooling obtained at one of the junctions, and I therefore prefer a form of apparatus in which this cooling is shown directly rather than as a differential effect only. In our apparatus a bismuth-antimony couple made of rods 8 mm in diameter is surrounded by a gas thermometer bulb 3.7 cm in diameter from which a tube of 2-mm internal bore extends down into a small beaker of colored water. Two heavy, rectangular brass rods soldered to the ends of the couple and fastened to a wooden stand act as supports and also as leads for the current. There is a real thrill in seeing that the gas actually contracts when the current is passed in the right direction. The wetting of the junction by the use of wicks dipped in ether has been advocated, and this doubtless enhances the effect but it also complicates the apparatus.

The Need for More College Instruction in Photography

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ALTHOUGH photography is a key profession, used today in almost every avenue of business and social life, giving employment to thousands of people, and using millions of dollars worth of materials each year, it has, until recently, been neglected by the colleges and schools. However, the histories of most professions show that many decades passed before education in any one of them became really thorough. Always, those who learned through hard experience have taught helpers or apprentices, who in turn passed their accumulated information to others in the next generation, until enough interest was generated to warrant forming classes for group instruction.

Photography, one of the youngest professions and the basis for several allied trades, is experiencing a spectacular growth, with progress in the past decade so rapid, and the demand for information so great, that it has run far ahead of educational facilities. The old-time professional photographer, whose knowledge and practices were somewhat sketchy and mysterious, is fast being replaced by younger men who demand training and information that is up to date and comprehensive. Rapid progress in commercial and illustrative photography in the past decade, and recent improvements in color photography require technically trained men of a caliber found only in technical colleges.

Modern developments in other professions also demand training in photography. A lawyer needs to know something about photography because it is used as evidence; journalists should be able to illustrate their own stories; engineers are helped if they are capable of making photographic records of their progress, finished work and research. Students in schools of commerce should learn how photography is used for making and preserving records of business. Agricultural students need a sufficient knowledge of photography to enable them to record livestock identification, agricultural topography and crop information. In architecture, photography is valuable for the reproduction of drawings, records of construction and presentations of finished work. The medical profession is awakening to the tremendous value of photography in preserving case records and illustrating methods of treatment, especially since the advent of color photography as represented by transparencies for lantern-slide material or visual inspection. Many physicians have, in spite of continued professional pressure, taken time to learn enough photography to help them in their work. Its use in many branches of science is not only vitally important but extensive. Often the ability to produce a photograph is less important than a thorough understanding of the use and application of photography in one's own profession or vocation.

In American colleges and universities there are at least 100,000 students who should be receiving some knowledge of photography as it is adapted to the specific needs of the various prospective occupations. This training usually should be designed to inform the student as to the type of photographs that will be most useful to him in his occupation. It should include sufficient technical information and practice to insure the ability to produce them, without going into the broad technical and practical training which would be necessary for those entering the photographic profession.

Aside from the needs of this great body of students, there is a great and growing need for a more thorough training of prospective high school teachers, particularly those in vocational high schools, who foresee the advantage of being able to handle classes in photography. Obviously these teachers should not have to undertake such instruction with only a limited amateur experience and such books as are available. A beginning has been made in the introduction of courses on the teaching of photography in normal training schools; but few properly trained instructors are as yet available for such work.

In the first World War, although even manufacturers of photographic supplies did double duty in the training of men, the start was late and

the time too short. As part of the present national defense program, thousands of men expertly trained as observers and ground men should be made available as quickly as possible.

In the professional field, a rapidly increasing need for thorough photographic instruction is developing because of the enactment in many states of a law which requires that a stringent examination in both theory and practice be passed before applicants are permitted to practice photography. Although this requirement will go far toward placing the entire photographic profession on a higher plane, the educational facilities by which prospective applicants may secure needed instruction, training and practice are as yet practically nonexistent. The poor craftsmanship so noticeable in various strata of the profession is largely due to the lack of proper training and educational advantages.

In the United States, approximately 20,000 studios engage in the practice of professional photography and the pursuit of allied trades, such as photo-finishing, retouching, photo-coloring and picture framing. While the number of persons in a studio is usually small, nevertheless, some of the larger studios give employment to as many as 100 people. Estimating the average number per studio to be 5, we find that approximately 100,000 persons are engaged professionally in the production of photographs.

Photography is a profession that has no retirement age limit; many photographers are still active at the age of 70, and continuous careers of 50 years in the profession are not uncommon. However, the indications are that the average career probably is not over 20 years, which means a country-wide annual need for 5000 replacements in personnel. When state examinations have become general, educational facilities of some kind will be needed for these 5000 people entering the professional field annually.

Most men in the profession are too one-sided in their training and experience to be useful as instructors; they know the practical side of their particular specialty, but many would be stumped by such terms as *gamma*, *sensitometry* and *p*H. The illustrator would not know how to teach subjects out of his line, and this is also true of the commercial specialist, the portraitist and the color technician. For example, none of those mentioned would be able to teach photomicrography, particularly when its separate technics were involved, as applied to metallurgy, crystallography, pathology, botany, entomology, zoology and numerous other fields. A number of private schools have sprung up, each under the leadership of some individualist who has been widely recognized for his speciality. For those who are desirous of learning only his methods, such schools serve the purpose but only that purpose; the instruction does not have the seemingly necessary objectives outlined in this article.

A few universities, colleges and technical schools have recognized the need for photographic instruction but only to a limited degree. The following list includes most of those that offer such instruction:

Barnard College.—The physics department offers a 3 credit-hour course, embracing the theories of optics as applied to photography and photomicrography; the principles of still and motion picture photography; infrared, ultraviolet and x-ray photography, and the theory of color photography. A 2 credit-hour advanced course, known as "Advanced laboratory work in special fields," is also offered.

Baylor University.—The physics department offers an introduction to photographic technic and its applications, but it is not counted toward either a major or a minor in physics, or toward the physical science requirements for the A.B. degree.

University of California.—A 1 credit-hour course (2 units) is given in the College of Applied Arts. Several 10-week courses on various aspects of photography are offered by the University Extension Division but carry no university credit.

Dartmouth College.—The physics department offers a one-semester, 3 credit-hour course on "Principles of photography," with prerequisites of physics and elementary chemistry.

University of Florida.—The industrial engineering department offers the following one-semester, 3-hour courses, extended over a period of 2 years: "Photographic chemistry" (prerequisites, organic chemistry and college physics, or suitable photographic experience); "Elements of photography;" "Principles of photography" (prerequisite, preceding course); "Advanced photography" (prerequisite, preceding course); "Professional photography" (prerequisite, preceding course). All these courses are elective and are open to any student who can meet the prerequisites.

University of Georgia.—A one-quarter elective course is given in the physics department, and a one-quarter semi-elective course, in the School of Journalism.

Hunter College.—A one-semester liberal arts course, one lecture and one 3-hour laboratory, is given in the physics department.

University of Illinois.—A one-semester course in press photography is offered to junior students in the School of Journalism for 2 credit-hours in the summer session and 3 hours for a semester's work; an optional laboratory period of 4 laboratory-hours per week is available for those who desire special help. A one-semester course in elementary photography given by the physics department, College of Liberal Arts and Sciences, is elective, with prerequisite of general physics and permission of the instructor.

Iowa State College.—A one-quarter elementary course (3 credit-hours) and an advanced course (2 credit-hours) called "Photography in scientific work," are given in the physics department; they are elective to all students. A new course in photography for journalists has been organized this year.

State University of Iowa.—The available courses are a two-semester, 2 credit-hour course in "News photography" in the School of Journalism and a "Summer short course in photography" of 3 days' duration.

Massachusetts Institute of Technology.—The following one-semester courses, offered in the physics department, are elective and open to students with suitable prerequisites: "Elementary photography," 2 lecture-hours and 1 preparation-hour with prerequisites of 2 years of physics, 1 year of general chemistry and mathematics through differential equations; "Advanced photography," 3 laboratory-hours and 2 preparation-hours with the preceding course as a prerequisite; "Motion picture photography," 1 lecture-hour and 3 preparation-hours with a prerequisite of the optics course. Some work in photography is required in the optics course.

University of Michigan.—The College of Engineering offers a basic one-semester, 2 credit-hour course, and an advanced one-semester, 2 credit-hour course in "Photography and camera surveying." They are open to students in various other divisions of the University on an elective basis.

University of North Carolina.—A one-quarter, 3 credit-hour course is given by the physics department as a general elective in any school of the University.

Oberlin College.—The two courses given in the College of Arts and Sciences are open only to major students in chemistry and are presented primarily as a working tool for the scientist. One is for 2 credit-hours in the first semester; the other, for 1 credit-hour in the second semester.

Ohio State University.—Five courses given in the College of Engineering may be elected by students from various colleges of the University. Two of these courses allow 2 credit-hours each per quarter; 2 are for 3 credit-hours each; one is for from 3 to 5 credit-hours. The percentages of total enrolment are distributed among 6 different colleges or schools as follows: Engineering, 33.0; Arts and Sciences, 18.8; Education, 17.1; Agriculture, 12.5; Graduate, 7.8; Pharmacy, 3.0.

University of Oklahoma.—The School of Journalism offers a one-semester, 1 credit-hour elementary course, a one-semester, 1 credit-hour course in "News photography" and a one-semester 2 credit-hour course in "Advanced news photography."

Rochester Athenaeum and Mechanics Institute.—The 3-year technical course cooperative with photographic industries in the second and third years, leads to technical and research areas of employment. The 3-year professional course, leads to professional practice, to sales and demonstration vocations with photographic industries, or to opportunities in the teaching field; first offered in 1930 as a 2-year course, it is now the most thorough and advanced program of its kind available anywhere.

University of Tennessee.—The entomology department gives a one-quarter, 3 credit-hour course which is open to juniors and seniors in the College of Liberal Arts.

Virginia Polytechnic Institute.—A one-quarter, 3 credit-hour elective course is given in the department of architectural engineering.

University of Wisconsin.—The physics department offers a one-semester, 3 credit-hour course, consisting of 2 lectures and one 4-hour laboratory period per week, at the University at Madison and in the Milwaukee Center. An additional noncredit lecture course of a less technical nature is offered in the evening at the Milwaukee Center.

It will be seen that the responsibility for such photographic training as is given is about equally divided between the colleges or departments of liberal or applied arts, engineering, journalism and physics. This would indicate either a difference of opinion as to the proper organizational set-up, or the element of chance as the result of individual interest. Although any expansion of facilities and instruction might properly occur in those departments in which the start has already been made, this could, in some cases, interfere sufficiently with the work already being offered to justify a fresh start in another department to service other interests. This might be particularly the case in the colleges of journalism, thus leaving the colleges of applied arts and engineering, and the departments of physics as the most logical organizational possibilities.

Five levels, or areas, of photographic instruction are needed, in each of which the instructional material will need to differ widely:

(1) *In high schools or vocational schools*, as an aid in vocational guidance work. Fundamental instruction and practice, with lectures on vocational aspects, are indicated.

(2) *In colleges and universities*, to meet fundamental and occupational needs in other professions. Lectures and illustrated case material, combined with as much fundamental laboratory work as time will allow, must suffice, and

will at least give the student a foundation upon which he can build later. The fundamental practice work can be taught by those who have had a general course in photography, such as is contemplated in class 3, but the lectures and case material would necessarily be provided by instructors of broad practical experience. If practicable, at least one lecture and one 3- to 4-hour laboratory period per week throughout one year should be provided. Postgraduate or special elective work might also be arranged in this area.

(3) *In normal schools, universities or colleges*, as summer school training for prospective teachers of photography in secondary or vocational schools. The instruction should include fundamental laboratory work lectures on the subject matter being practiced, and lectures on psychological and practical methods of presenting the instructional material to younger students.

(4) *In colleges and universities*, as advanced training for those who wish to teach advanced photography, who desire to enter the professional field or who are already in the professional field but require certain specialized training. Here certain occupational goals must be established, with appropriate prerequisite training; for example, instructor in high school; instructor in normal or teacher-training school; laboratory assistant; general or specialized professional photographic practitioner.

The instruction in this area may be as broad or specialized, or as technical or practical as may seem to be dictated by the occupational goal. The amount of time and study which should be devoted to any particular subject or group of subjects in the curriculum is necessarily a matter for a great deal of conscientious planning by people who have had extensive experience. It is not feasible to calculate the various elements needed in a comprehensive and intensive study of photography from an entirely academic viewpoint. Such subjects as physics, mathematics and chemistry must be adapted to photographic requirements; the standard college courses in these areas contain much inept material and lack much that is needed. Among the requisites is a thorough knowledge of sensitized materials, as taught in sensitometry, with appropriate practical instruction in their use in photographic technics for both black and white and color photography.

Since photography must make use of the same principles of art as painting, or drawing, or any other artistic medium of expression, study of these principles should be a continual part of the training experience. In addition, those students whose goal is the professional field should study design and layout in advertising, or portrait drawing, or both.

Those students who are preparing for a professional career should also receive pertinent and practical training along business lines, particularly principles of advertising, accounting and studio management. The entrance requirements for the professional training program should be similar to those for a college of engineering, and the program itself should require three or, preferably, four years.

Students who are preparing for a teaching career should hear special lectures by practical and experienced people in various other professions on the specific uses of photography in their particular fields. As many case-records as possible should be studied, in which photography was an important key to the solution of the problem. If the student intends to enter high school teaching, he should have satisfied the requirements of his state for teaching before matriculating in the photographic course. He must have an A.B. degree and, in some cases, a master's degree, and must have taken certain teacher-training courses.

For those students who enter any of the aforementioned training areas with little or no previous experience, a curriculum that is well balanced between the technical and practical needs can be planned fairly easily. But, when a study is made of the varying qualifications possessed by those who will seek to prepare for examinations in states where a license is required, a variety of opinions as to requisites will be encountered. Such training will necessarily be of fairly brief duration, and every candidate will want to set his own entrance requirements and will seek credit for various practical experiences. The only apparent solution is to make definite decisions in conference with the state examining board and adhere to them. Although the training for this purpose will have to be limited and intensive, arrangements might desirably be made in summer school for students who have qualified for a license to return for specialized or advanced training.

(5) *In every institution where facilities are available*, training of men for purposes of national defense, under the direction of the Army or the Navy. For example, more men will be needed in the industrial field as a result of the demand for military supplies. Curriculum problems will doubtless be slight, because training plans have been well worked out in existing Army and Navy schools of photography, and competent advice and assistance will be available.

The writer realizes that it will be some time before such training in photography as he visualizes will be generally available, but it is definitely on its way. The demand for such training and for trained professional men is keeping pace with the popularity of photography. To be sure, much of the upcurve has been in the amateur field, but the professional area has reflected the same trend, particularly in commercial illustration, where, during the past 15 years, the increase in practice has been about 200 percent, based on the number of illustrations made by photography as compared with other mediums of expression.

Everywhere the question is being asked: "Where can I obtain adequate training for the photographic profession or for the teaching of photography?" In our institution, students from Canada, Hawaii, India and nearly every state in the Union have received or are receiving training.

Owing to definite limitations as to numbers, more applications each year are necessarily postponed or rejected than can be accepted. Many have to wait their turn for acceptance until the following year. This condition will soon apply to any institution that offers similar training.

The author is indebted to Dr. W. W. Charters of the College of Education, the Ohio State University, Dr. Lawrence L. Jarvie of Rochester Athenaeum and Mechanics Institute, and faculty members of many colleges for assistance in the preparation of this article.

The Present Status of Physics in Negro Colleges

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RECENT studies[1-3] have been made of chemistry and science survey courses in Negro colleges. The present study is concerned with the status of undergraduate and graduate physics. The data were obtained from questionaries mailed to the heads of the departments of physics in 45 Negro colleges, and by analysis of the catalogs and bulletins of these colleges.

The colleges included in the study were selected at random; the only criterions for inclusion were that each college be a four-year, degree-granting institution and that it be accredited by some accrediting agency, regional or state. Fourteen of the institutions are publicly controlled colleges, 3 are publicly controlled teachers colleges, and 28 are privately controlled colleges. Two are men's colleges, and two are women's colleges. The colleges were selected from 17 states and the District of Columbia as follows:

Alabama.—Miles Memorial College; The State Teachers College; Talladega College; Tuskegee Institute.

Arkansas.—Agricultural, Mechanical and Normal College.

District of Columbia.—Howard University; Miner Teachers College.

Georgia.—Clark University; Morehouse College; Paine College; Spelman College.

Kentucky.—Kentucky State College; Louisville Municipal College.

Louisiana.—Dillard University; Southern University; Xavier University.

Maryland.—Morgan State College.

Mississippi.—Tougaloo College.

Missouri.—Lincoln University.

North Carolina.—Agricultural and Technical College; Bennett College; Johnson C. Smith University; Livingstone College; North Carolina College; Saint Augustine's College; Shaw University.

Ohio.—Wilberforce University.

Oklahoma.—Colored Agricultural and Normal University.

Pennsylvania.—Lincoln University.

South Carolina.—Allen University; Benedict College; Claflin College; State Agricultural and Mechanical College.

Tennessee.—Fisk University; Lane College; LeMoyne College; Tennessee Agricultural and Industrial State College.

Texas.—Bishop College; Prairie View State Normal and Industrial College; Wiley College.

Virginia.—Hampton Institute; Virginia State College.

West Virginia.—Bluefield State Teachers College; Storer College; West Virginia State.

Seventeen of these colleges were given a rating of *A*, and 12 a rating of *B* by the Southern Association of Colleges and Secondary Schools; 3 were accredited by the North Central Association of Colleges and Secondary Schools, 2 by the Association of American Universities, 2 by the Middle States Association of Colleges and Secondary Schools, and 3 by the American Association of Teachers Colleges. These colleges were also accredited by various state boards.

The Curriculums

What problems does the inclusion of physics in the general curriculum present? The following quotations from statements by instructors throw some light on this question:

[1] Woodson, "A survey of chemistry curricula in Negro colleges," J. Negro Ed. **8**, 644–8 (1939); "The present status of chemistry in Negro colleges," J. Chem. Ed. **17**, 111–16 (1940).

[2] Wallace, "Chemistry in Negro colleges," West Virginia State College Bull. April, 1940.

[3] Blanchet, "Survey of natural science survey courses in Negro colleges," Sci. Ed. **23**, 265–74 (1939).

Few high schools in the state teach physics. Our students are largely preparing for the teaching profession. Most of the students have chosen other fields before they realize that physics exists, and the college organization makes shifts difficult. Our students dodge science largely because of the recognition of mathematical weakness, and therefore dodge physics most.

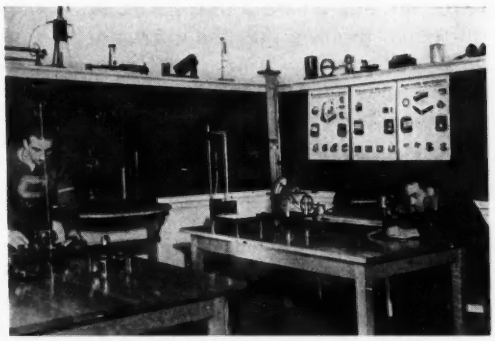
We are particularly interested in a well-developed applied physics instructional plan in preference to a general physics course, as the State Department of Education is now emphasizing biology to the exclusion of chemistry and physics in its high school curriculum for Negroes. Our reorganization in which physics is worked into the curriculum as applied physics thus seems to be the only way to keep it in the curriculum.

Physics is not offered in many high schools in the South, and apparently is being forced out of the high school curriculum. Less emphasis is being placed on physics in the college; it is offered mainly as a service course to meet the needs of premedical and certain other professional groups. Survey courses in science are taking the place of the traditional science courses. The student does not elect science courses because of their difficulty, and because they demand a substantial mathematical background.

TABLE I. *Courses offered in physics departments.*

COURSE	No. OFFERING	PERCENT
General physics	45	100
Electricity and magnetism	22	49
Modern physics	16	36
Optics	15	33
Household physics	14	31
Theoretical mechanics	13	29
Advanced laboratory	11	24
Radio	9	20
Heat	7	16
Mechanics and heat	5	11
Theoretical physics	4	9
Problem course	4	9
Physical measurements	4	9
Elementary physics	3	7
Sound	3	7
Photography	3	7
Astrophysics	2	4
A.c. and electronics	2	4
General thermodynamics	2	4
Electron physics	2	4
Kinetic theory	2	4
Agricultural physics	1	2
Sound, heat and light	1	2
Sound and light	1	2
Advanced physical measurements	1	2
Introduction to mathematical physics	1	2
Differential equations of mathematical physics	1	2
Theory of the atom	1	2
X-rays	1	2
History of physics	1	2
Reading course	1	2
Special topics	1	2
Seminar	1	2

Nineteen colleges, or 42 percent of those studied, offer a major in physics. The number of semester-hours of physics required ranges from 24 to 30. Mathematics through calculus is required. Only 3 of the departments require physical chemistry of the majors; the others require general inorganic chemistry.



General physics laboratory, Storer College.

Table I lists the courses offered in all physics departments. Thirty-three different physics courses are noted. However, 20 percent or more of the colleges offer only 8 courses. These are general physics, electricity and magnetism, modern physics, optics, household physics, theoretical mechanics, advanced laboratory and radio. Eight colleges, or 18 percent, offer only general physics. Fourteen colleges, including the two women's colleges, offer household physics, usually as a required subject for home economics majors. One institution gives an undergraduate degree in applied physics; its physics courses are "not the unapplied routine of a liberal arts institution, but basic applied physics after the general course of one year."

The textbooks used in the various general physics courses include those by Black, Blackwood, Foley, Kilby, Knowlton, Millikan, Gale and Edwards, Randall, Williams and Colby, Stewart, and Williams.

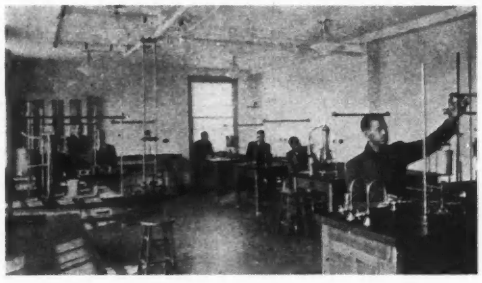
THE FACULTIES

The physics department of a Negro college may be handicapped by limited funds, lack of properly prepared students and few opportunities

for employment of its graduates; but its instructional staff is adequately trained.

There are 56 physics instructors in the 45 institutions studied. Thirty-six colleges, or 80 percent, have 1 instructor of physics, 7 have 2 instructors, and 2 have 3 instructors.

A serious problem that the instructors face in many of the colleges studied is the number of



Physics laboratory, North Carolina College.

departments in which they must give instruction. Subjects which they must teach along with physics are, in the order of their approximate frequency, mathematics, physical science survey, chemistry, biology, engineering, geology, astronomy and education. We may safely assume that, if an instructor directs his efforts wholly to instruction in one field, it is in all probability the subject of his specialization either in graduate or undergraduate study. However, if he teaches three or more subjects, at least one of these is likely to be outside his major or minor preparation.

In the 45 colleges studied, 9 staff members (16 percent) have the Ph.D. degree, 41 (73 percent) the master's degree and 6 (11 percent) the bachelor's degree. It is not possible to report the extent of work accomplished beyond the highest degree reported. The possessor of either two bachelor's or two master's degrees is given credit for only one.

Table II shows the universities at which graduate degrees were earned. Five instructors hold master's degrees from Negro universities. It is also interesting to find that 22 instructors (49 percent) received their bachelor's degrees from Negro colleges and continued their work for their advanced degrees in outstanding universities.

Faculty inbreeding has long been regarded as one of the problems involved in the organization of a competent academic staff of a university or college. Three types of inbreeding in physics departments of Negro colleges were noted: (1) the instructor who had received the bachelor's degree as his highest degree from the institution employing him, (2) the instructor who had received his bachelor's degree from the institution employing him but his higher degrees elsewhere, and (3) the instructor who had received the bachelor's and master's degrees from the institution employing him but the doctor's degree elsewhere. The latter two types are not necessarily undesirable.

Six physics instructors (about 11 percent of the total) are teaching in colleges where they received all or part of their training. Two of these instructors have distinguished themselves in the scientific world and are heads of their respective departments. Three instructors, holding a bachelor's degree as their highest degree, are teaching in the institution which granted the degree. If this inbreeding is the natural result of opportunities to select from the students the persons best qualified to realize the objectives of the institution, and has resulted in a staff that accomplishes the purposes of the institution, the fact of inbreeding is probably of little significance.

TABLE II. *Institutions in which graduate degrees were earned.*

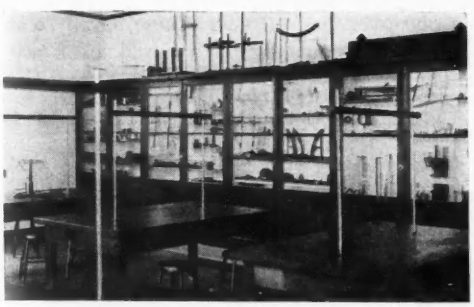
INSTITUTION	Ph.D.	MASTER'S
Atlanta		2
Boston	2	1
Chicago		3
Cincinnati	1	
Clark (Worcester)		1
Columbia		4
Cornell	3	1
Harvard		1
Howard		3
Indiana		2
Iowa		4
Iowa State		3
Massachusetts Institute of Technology		1
Michigan	2	3
New York		1
Northwestern		1
Ohio State		1
Pennsylvania	1	3
Pennsylvania State		1
Pittsburgh		1
Purdue		1
Colleges not named		3
Total	9	41

It can be concluded that the factor of inbreeding in the Negro college physics departments is of little significance.

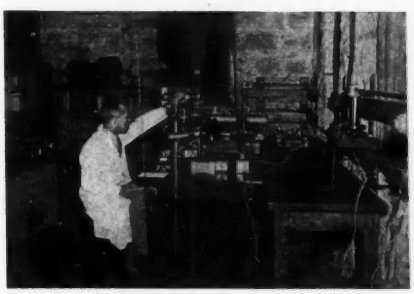
Graduate Physics

Three Negro institutions offer work in physics leading to a master's degree. They are Fisk University, Howard University and Virginia State College.

The physics staff of Fisk University consists of two members. One holds the Ph.D. degree from the University of Michigan, has had 12 years experience as a consulting and research physicist, and has been in his present position 10 years. The other holds the master's degree from the University of Michigan. At Howard University there are three physicists. One holds the master's degree from the University of Chicago and has had additional work at the National Bureau of Standards and the University of Pennsylvania. One has the master's degree from Columbia



General physics laboratory, The State Teachers College, Montgomery, Alabama.



A corner in the physics research laboratory, Fisk University.

University, with additional work at the National Bureau of Standards. One holds the Ph.D. degree from Cornell University. In Virginia State College two members of the physics staff hold Ph.D. degrees from Cornell University, and one has a master's degree from Pennsylvania State College.

The laboratory facilities for physics at each of these institutions is valued at more than $20,000. Howard University has a physics library of 1500 volumes.

Activities of Association Chapters

District of Columbia

THE second meeting of the academic year 1940–1941 was held at George Washington University, on February 14. Fifteen members and guests were present. Thomas B. Brown, of George Washington University, gave an extensive report on the annual meeting of the Association held in Philadelphia. He also demonstrated a two-dimensional gas model and showed motion pictures of the model in operation.

George D. Rock, of Catholic University, has been designated as Acting President to replace Glenn L. Rouse, who is absent on defense work.

Oregon

The 27th meeting of the Oregon chapter was held at Willamette University, Salem, February 22, 1941. The addresses heard were:

The traffic safety problem. S. R. Church, *Director of Traffic Safety, State of Oregon.*

The use of the sound level meter. W. V. Norris, *University of Oregon.*

Demonstration of selected experiments. A. E. Caswell and D. Hunter, *University of Oregon.*

The physical phases of fluorescent lamps, with demonstrations. J. C. Garman, *Oregon State College.*

Other features of the meeting were a tour of the State Testing Laboratories and a business session. Plans for a proposed Student Science Conference were presented by M. A. Starr, chairman of the committee on prize awards.

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

16. The *Tribuna di Galileo* in Florence

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California Institute of Technology, Pasadena, California

ON the second floor of the Museum of Physics and Natural History which adjoins the Pitti Palace in Florence, Italy, is an exquisite temple dedicated to the memory of GALILEO—a shrine dear to the heart of every teacher of physics who has ever visited it, whether he be Italian or English, German, French, Dutch or American. As J. J. FAHIE has so well written in his eulogistic *Memorials of Galileo Galilei*,[1]

> To my mind the Tribuna di Galileo is one of the noblest, certainly, the most evocative and inspiriting monument ever raised to the memory of mortal man. Those who enter this little temple in a proper spirit and ponder over its contents and the lessons they teach, surely, will not depart without new conceptions as to the value of life—perhaps, with new resolves to do something (however little) to make the world around them better than they found it. . . .
>
> If an intense desire of being useful to mankind is everywhere worthy of honour; if its value is increased when united to genius of the highest order; if we feel for one who, notwithstanding such titles to regard, is harassed by cruel persecution; then none deserves our sympathy, our admiration, and our gratitude, more than Galileo.

This shrine, which was dedicated in 1841, consists of a rectangular vestibule, one side of which opens into a smaller square hall, which in turn opens into a still smaller semicircular tribune in whose center stands a heroic statue of GALILEO. Plate 1 is a view of the central hall and the tribune taken from the vestibule. As one stands in this position the entrance to the vestibule is on the right and at one's back is a fine stained-glass window. The walls of all three rooms are lined with variously colored Tuscan marble and are profusely decorated with frescos, medallions, busts and drawings, carved in low-relief, and illustrative of the discoveries and inventions of GALILEO and his immediate followers.

The large frescos—two in lunettes above the end walls of the vestibule, two in the lunettes above the side walls of the central hall, and three in the compartments of the domed ceiling of the tribune—summarize in pictorial form (1) the state of science before GALILEO, (2) his own more important contributions, and (3) how his spirit and work lived on in the discoveries of his immediate successors and of succeeding generations. Beginning with the one that faces the visitor on entering the vestibule and ending with the one over the entrance, these seven frescos picture with rare simplicity and even rarer insight:

1. The state of mechanics at the beginning of the sixteenth century
2. GALILEO making experiments on the laws of falling bodies

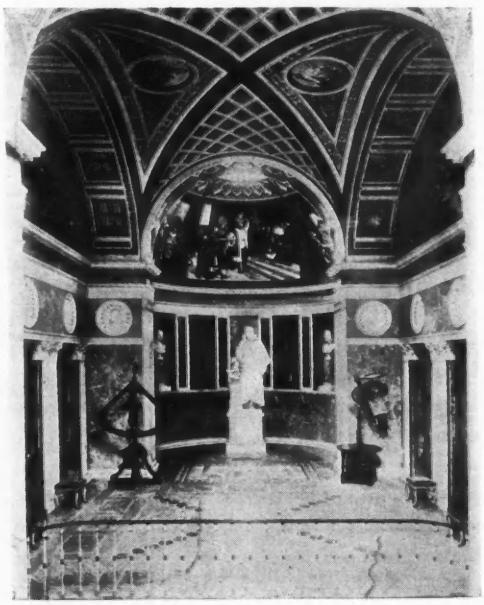

PLATE 1. VIEW OF THE *Tribuna di Galileo* FROM THE VESTIBULE.

[1] This unique collection of portraits, paintings, medals, medallions, busts, statues, monuments and mural inscriptions was privately printed at the Courier Press, Leamington and London, 1929. It is worthy of note in these days of intense national antagonisms that this "labor of love" was performed for an Italian by an Englishman.

3. GALILEO discovering the isochronism of the pendulum
4. GALILEO presenting his telescope to the Republic of Venice
5. GALILEO imparting his discoveries in dynamics to TORRICELLI and VIVIANI
6. The Accademia del Cimento continuing the work
7. VOLTA explaining his electric pile to Napoleon and the members of the Institute of France.

All seven of these frescos will be reproduced and discussed in detail in the "Reproductions" which are to follow in this series.

Ten smaller paintings symbolizing nature, truth, perseverance, physics, philosophy, astronomy, geometry, mathematics, hydraulics and mechanics are scattered over the vaulted ceilings, and on the pilasters are 14 white marble medallions of members of the Accademia del Cimento and other Italian scientists. On the face of the arch which joins the tribune to the central hall, GALILEO's five celestial discoveries—the moons of Jupiter, the sunspots, the mountains of the moon, the phases of Venus, the rings of Saturn—are indicated in gold-relief on a blue background. Below these the instruments invented by GALILEO and used by him in his discoveries are intaglioed in the marble. Similarly, on the face of the arch connecting the central hall with the vestibule, there is depicted the emblem of the Accademia del Cimento and the instruments which were used in the Academy's experiments.

The white marble statue which stands in the center of the tribune is the work of ARISTODEMO COSTOLI. It was executed about 1840 and shows GALILEO in a flowing robe with his right hand resting upon a manuscript placed on a half-column (Plate 2). The manuscript is spread open to reveal some of the diagrams from the *Two New Sciences*.

In the semicircular wall of the tribune are six niches; four of these contain busts of CASTELLI and CAVALIERI, TORRICELLI and VIVIANI, the two first and the two last disciples of GALILEO. The remaining two niches are glassed in and contain two of GALILEO's later telescopes, the object glass of the telescope with which he made most of his astronomical discoveries, his geometrical and military compass, one of his armed loadstones (weighing only 6 oz but supporting 10 lb of iron in the form of a tomb), and the index finger of his left hand. In the large cases lining the walls of the central hall and vestibule are displayed many interesting specimens of the instruments used by the Accademia del Cimento. Of these the world-famous thermometers and other fine examples of Florentine glasswork are the most interesting. Four instruments of large size stand in the four corners of the central hall: a brass astrolabe, an odometer, a movable dial by RINALDINI, and the large crystal lens of BREGANS of Dresden with which AVERANI and TARGIONI-TOZZETTI, and later HUMPHRY DAVY, made experiments on the combustion of diamond and other precious stones.

PLATE 2. STATUE OF GALILEO IN THE *Tribuna di Galileo*. (From an engraving in the *Descrizione della Tribuna alla Memoria del Galileo*, by Giovanni Rosini, Florence, 1841.)

NOTES AND DISCUSSION

A Nonresonant Method of Measuring the Wave-Length of Sound

THIS is a method of studying the wave-length of sound without the aid of resonance.[1] Two similar velocity microphones are connected in series and feed into the same amplifier which ends in an output voltmeter.

The apparatus is shown in Fig. 1. The two microphones

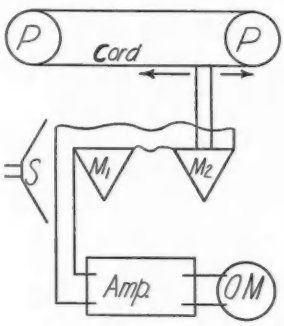

FIG. 1. Diagram of the apparatus.

M_1 and M_2 are arranged on a line out from a speaker S which furnishes sound of constant frequency. One microphone is fixed in location and the other, M_2, is arranged so that it may be pulled by the cord to which it is attached to any desired distance from the fixed microphone. The remote control allows the observer to move the microphone while reading the output meter without disturbing the sound pattern by moving into it himself.

The two microphones, depending upon whether they are connected additive or subtractive, measure the vector sum or difference of the particle velocities at their respective positions. Thus measurements of wave-lengths of both standing and traveling waves can be made.

Some qualitative results are shown in Figs. 2–3. Figure 2(*a*) shows an ideal standing wave distribution produced in air when the sound from the speaker at S strikes a wall and is reflected. If one microphone alone is connected to the amplifier and moved from S to the wall, it will register an output as plotted in Fig. 2(*b*). This shows the familiar nodes and loops spaced one-half wave-length apart. If then the two microphones are connected in series additive (so that their ribbon movements produce voltages in the same direction in the series circuit) and one microphone is kept at a fixed location, say at F, while the other is moved toward the wall, the results plotted in Fig. 2(*c*) are obtained. This curve shows the maximums a full wave-length apart because of the fact that the particle vibrations are 180° out of phase in adjacent loops of the standing wave pattern and hence cancel each other when picked up by the two microphones. If the two microphones are connected subtractive, the results are those plotted in Fig. 2(*d*), which is 180° out of phase with curve (*c*).

The results are most interesting when the sound is allowed to travel out in free air (out of doors), where there are no standing waves. If only one microphone is connected and moved out from the sound source, the gradually decreasing intensity will register in the output meter as in Fig. 3(*a*). Now suppose the two microphones are connected in series additive, one being kept at any position F, Fig. 3(*b*), while the other is moved outward. If the output is plotted, maximums and minimums appear in the output, each maximum a full wave-length from the next maximum. The explanation is that, regardless of the location of the fixed microphone, the sum of the outputs of the two microphones will be a maximum when they are either together or an integral number of full wave-lengths apart; that is,

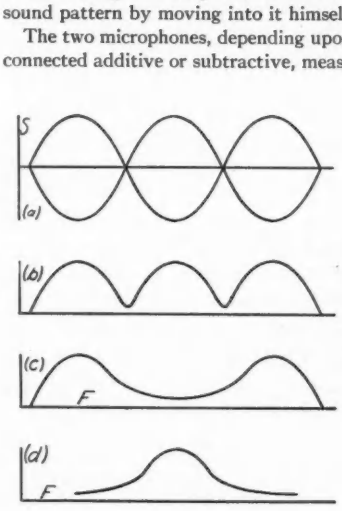

FIG. 2. Intensity plotted as a function of distance from the source: (*a*) ideal standing wave; (*b*) measured with one microphone; (*c*) measured with two microphones connected in series additive; (*d*) measured with two microphones connected in series subtractive.

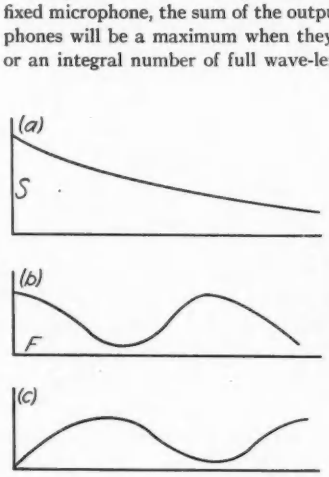

FIG. 3. Sound measured in free air: (*a*) intensity measured with one microphone; (*b*) measured with two microphones connected in series additive; (*c*) measured with two microphones connected in series subtractive.

the sum will be a maximum when the movable microphone reaches the point where the particle vibration is in phase with the vibration at the fixed microphone, which is exactly a wave-length; hence the distance between the two microphones is equal to the wave-length of the sound. Similarly, if the microphones are connected subtractive, the output reaches a maximum when the two microphones are an odd number of half wave-lengths apart, as shown in Fig. 3(*c*).

In practice, the best way to make measurements is to connect the microphones subtractive, because the intensity then starts at a minimum when they are together and near the source, and increases to a maximum at half wave-length separation where the intensity would normally be falling off because of greater distance from the source. Thus the range of the amplifier and meter is not taxed so severely.

This method of studying wave-lengths was developed at Indiana University under the direction of Professor R. R. Ramsey.

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Ohio University,
Athens, Ohio.

[1] First reported by the author in Proc. Indiana Acad. Sci. **46**, 180–183 (1937). A similar method is described by Colwell, J. Frank. Inst. 228, 251 (1939).

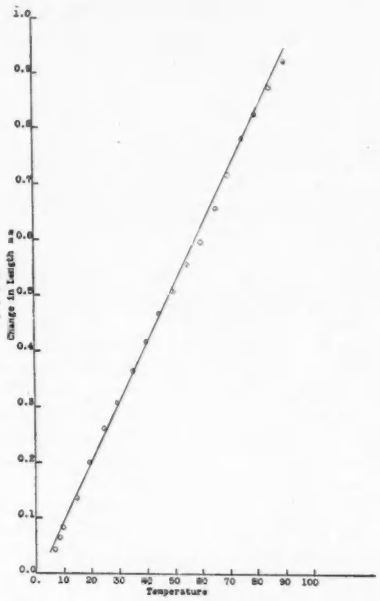

FIG. 2. Change in length of a copper bar as a function of temperature.

Modified Thermal Expansion Apparatus

AN apparatus for the demonstration of thermal expansion, which is in general use in both school and college laboratories, consists of a rod of the metal to be tested surrounded by a metal jacket through which water or steam may be passed. The student may obtain a fairly accurate determination of the difference in length between the rod at 0° and 100°C by flowing ice water—then steam—through the jacket. From this he may calculate the average coefficient of thermal expansion. If he attempts to make determinations at intermediate temperatures, the results are usually so irregular that his graph, if he does not give up in disgust or fake his results, looks more like the path of a Brownian motion than a straight line. Besides, the setup is messy and the student feels it to be unworkmanlike.

Since the verification of the approximately linear relationship seemed more important than the measurement of a numerical constant, an attempt was made to modify the apparatus to allow this to be accomplished, and to eliminate the untidiness at the same time.

The apparatus illustrated in Fig. 1 is being used successfully in our freshman laboratory. The circulating pump *A* is from the cooling system of an automobile and was obtained at small cost from an automobile wrecking firm. In our apparatus it lifts water through a height of 23 cm at the approximate rate of 1.5 l min^{-1} when driven by a $\frac{1}{3}$-hp motor at 1700 rev min^{-1}. At the suggestion of Doctor O'Day, of this department, we are using a cheap, low-reading voltmeter as a galvanometer, rather than the usual bell to indicate contact between the micrometer screw and the rod. Thus noise is eliminated and the apparatus has a more businesslike appearance, a matter of some psychological value.

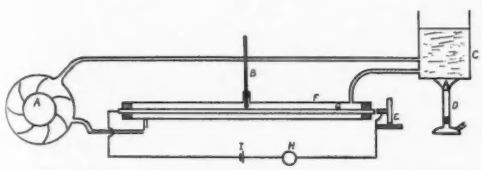

FIG. 1. Diagram of apparatus. *A*, pump; *B*, thermometer; *C*, tank; *D*, burner; *E*, micrometer; *F*, jacket; *H*, galvanometer; *I*, dry cell.

The graph in Fig. 2 was made by a pair of students during a regular three-hour laboratory period. The rod was of copper, and the coefficient of linear expansion calculated from the slope of the graph is 1.76×10^{-5} deg^{-1}. The fact that the determinations made with this apparatus are in respectable agreement with the handbook values[1] is of less importance than the striking demonstration which Fig. 2 presents of the linear relationship between the length of the rod and its temperature. Still more important is the improved attitude of the students, who are eager to work with a neat piece of equipment and get results in accord with those of experienced workers in the field.

Such irregularities as still exist are probably largely attributable to inaccuracies in the micrometer screw and unevennesses of the contact surfaces.

HARRY E. WOLF

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Portland, Oregon.

[1] 1.41×10^{-5} to 1.78×10^{-5} deg^{-1} in *Handbook of chemistry and physics* (ed. 14), p. 838.

Common Misunderstanding of Newton's Synthesis of Light

IT is a remarkable fact that in most textbooks of physics, as well as in some of the well-known treatises on light, Newton's famous recomposition of the colors of the spectrum is erroneously described, and that the description is often accompanied by an impossible diagram. The statement is usually something like that of P. G. Tait in the ninth edition of the *Encyclopædia Britannica:* "If a second prism of the same glass, and of the same angle as the first, be placed in a reversed position behind it, the effect of the two would be simply that of a plate of glass with parallel faces; the emergent rays would each be parallel to its original direction, and there would be no separation of the colors. The reversed prism would therefore undo the work of the first prism. Then we should have no dispersion, but we should also have no refraction." Similarly in the latest edition of the *Encyclopædia Britannica*, C. G. Darwin writes: "Newton showed that if the light passed through a second prism reversed, the colored lights would recombine into white."

Unfortunately, neither of these statements is wholly true, and where similar errors are committed by writers of textbooks, the accompanying diagram is equally fallacious. It shows the original narrow beam of white light diverging through the first prism A, as in Fig. 1, and then between the prisms (usually shown separated) the rays are drawn either incorrectly parallel or correctly diverging. If the latter, all is well up to this point. But now on entering the second prism B of such a diagram, the rays suddenly discover that the prism is inverted (how do they know it?) and *converge* through the glass to emerge in a beam of white light. In helping perpetuate this fallacy, the writer is guilty with all the rest and has only very recently discovered the error of his ways.

The truth of the matter is that the rays after entering the second prism B continue to *diverge*, as shown in Fig. 2; apparently Newton never claimed that they did anything else. A calculation for 60° flint glass prisms and C and F light shows that, with minimum deviation of C light, the diverging angle in either *prism* is about 24′, while between them it is nearly 2°. The rays emerging from prism B are parallel to the original beam and to each other. Their

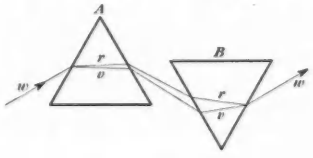

FIG. 1. Incorrect diagram.

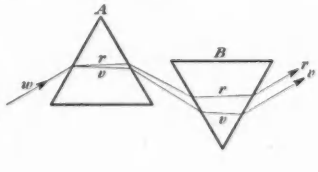

FIG. 2. Correct diagram.

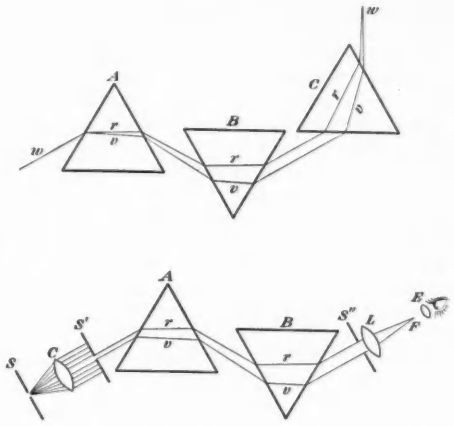

FIG. 3 (above). A Newtonian method for recombining the colors.
FIG. 4 (below). A simple demonstration of resolution and synthesis.

linear separation depends, of course, on the distance traveled through glass, and still more so on the length of the air path between prisms where the angular divergence is five times as great as in the glass. That the paths of the red and violet rays shown in prism B must be parallel to the corresponding rays in A can be rigorously demonstrated, though it seems too obvious to call for a formal proof.

It is difficult to understand why Newton has been accused of a fallacy which his diagrams do not even suggest. But it is only fair to call attention to the fact that if the source is fairly wide and the beam of parallel rays entering A is not the narrow pencil usually described and depicted, the correspondingly broad band emerging from B would be white except at its edges. These would be colored red and violet, and since the rays continue to diverge between the prisms and through B, the separation of the colors would steadily increase with increasing separation of the prisms and with increasing thickness of both prisms, while the white center would tend to vanish. So even with broad beams the second prism does not act as a recombining agent, as has been inferred from a misunderstanding of Newton's experiments. Actually he did recombine the spectral colors in a variety of ways but not with an inverted prism. Perhaps the neatest of these methods was to use a third prism C, as shown in Fig. 3. This really does recombine the parallel colored rays emerging from B.

Another method, which the writer has found very satisfactory, is illustrated in Fig. 4. The parallel beam emerging from B is recombined by the objective L of an ordinary spectrometer telescope to form a white image of the slit S at the principal focus F. This image is then examined by means of the ocular E in the usual manner. The slit S' limits the light emerging from the collimator lens C to a narrow beam of parallel rays, as indicated. If a third slit S'' is placed in front of the telescope objective and narrowed to admit only a small portion of the beam, the image is correspondingly colored, and by moving the slit across

the lens, one observes a beautiful series of approximately monochromatic "lines" throughout the entire range of the spectrum.

HENRY A. PERKINS

Trinity College,
Hartford, Connecticut.

A Modification of the Vibration Source for Melde's Experiment

A SIMPLE and convenient vibration source of variable frequency for Melde's experiment was recently described by Wold and Studer.[1] The purpose of this note is to propose a slight modification of that device, which the authors have found to result in somewhat smoother operation.

The apparatus shown in Fig. 1 is essentially the same as

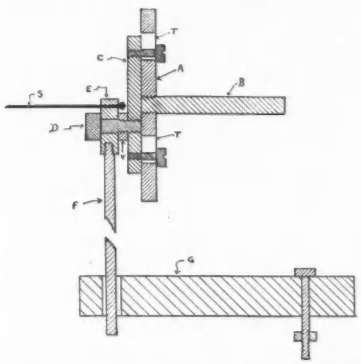

FIG. 1.

that of Wold and Studer. A disk or block of metal A is secured to the shaft B. The metal block C is bolted to A, preferably through slots T, which permit variation of the radius of the eccentric. The steel bolt D is rigidly fastened to C by the steel nut V, the shaft of the bolt being just long enough to permit carrying the steel block E. The only bearing surfaces are between the block E and the bolt and nut. One edge of E is drilled to take the cord S in which the standing waves are to be produced.

The modification consists in the method of preventing the rotation of the block E. This is necessary, of course, in order that the cord will not be twisted. Following Wold and Studer, this was first accomplished by fastening a rubber band or weight to a rod as at F in the figure. A considerable improvement was obtained by threading a $\frac{3}{16}$-in. rod F, about 7 in. long, into E, the other end of the rod passing through a $\frac{5}{16}$-in. hole in a $\frac{3}{4}$-in. wood block G and moving up and down like a piston rod. The resulting apparatus is exceedingly smooth and quiet in operation, and no wear has been detected after considerable use.

The wood member G can easily be bolted to the base of the rotator and removed when the rotator is used for other purposes.

GEORGE D. ROCK
ALBERT MAY

The Catholic University of America,
Washington, D. C.

[1] Wold and Studer, Am. J. Phys. 8, 165 (1940).

The Poundal Again

MANY articles have been written concerning the poundal and also concerning the absolute and gravitational system of units in mechanics. But even with the knowledge that the subject may be considered monotonous by some, I venture to bring it up again for the sake of the thousands of students who start the study of physics each year.

I shall first give the method I use in dealing with the absolute and gravitational systems, a method used by many, I am sure. From the special form of Newton's second law, $F=ma$, the dyne is defined. Gravitation is then very briefly discussed so that one may write down the relation $W=mg$. The student readily sees why $W \propto m$ in a given locality and, hence, why it happens that the names of mass units are used for new force units, and vice versa; that is, why the pound is taken as a unit of mass in the English system and the gram as a unit of force in the metric system, although strictly speaking the gram is a unit of mass and the pound a unit of force.[1] Next, the poundal is defined and then gravitational and absolute systems of units mentioned. The student is then advised to use the absolute system whenever the equation or equations used in a problem involve both forces and masses, and the following tabulation is given:

QUANTITY	METRIC	ENGLISH
force	1 dyne	1 poundal
mass	1 gm	1 lb
distance	1 cm	1 ft
velocity	1 cm/sec	1 ft/sec
acceleration	1 cm/sec^2	1 ft/sec^2
time	1 sec	1 sec

F (in dynes) $=F$ (in grams) $\times 980$, F (in poundals) $=F$ (in pounds) $\times 32.2$, where 980 and 32.2 are the numerical values of the acceleration due to gravity in a specified locality.

In this way the two systems of units are parallel, and when rotational motion is taken up, the extension to include torque and moment of inertia follows naturally. Furthermore, the student has no trouble in statics; the gram as a unit of force offers no more difficulty than the pound as a unit of force.

I realize that I have probably not satisfied those who advocate the dropping of the poundal from use. Are we, however, more justified in using force in grams than we are force in poundals? Those who object so strenuously to the poundal use grams of force in experiments such as the force board, a loaded rod, uniform motion on the inclined plane, and so forth, and even use grams of force in kinetics. I have heard as an objection to the poundal that it is not "used" and this objection can certainly be defended. I wonder how many physicists have ever measured a force directly in dynes and, consequently, if objection could not, with good reason, be raised to its use on the ground that it is not "measured" or even "used."

Of course, if a textbook is written using the cgs (or mks) units only or the fps units only, the absolute system can be used for the former and the gravitational system for the latter and there need be no confusion.[2] But in an introductory general physics course this is not done. We may have in the same set of problems pounds force and pounds mass, grams force and grams mass; we may have an attempt to distinguish between pounds mass and pounds

force by "lb." and "pd"; in one problem a mass of 50 g is given; in the next it may be stated that a block weighs 3 kg, and similarly for mass and weight in pounds. All this confuses a student, and it is for this reason that I have brought up the question of the poundal again. I have taught first-year college physics avoiding the poundal but have come to use the method just outlined as the one that causes least confusion. Others may not have had the same experience. In any event, judging from oral and written discussions, the situation is not what it should be. What is the remedy? Is there one? Is not the American Association of Physics Teachers an organization ideally constituted to consider the situation? A symposium on the teaching of mechanics in the first-year general physics course would, no doubt, prove quite worth while. Such a discussion might show the desirability of uniformity of definition; for example, I am sure there are some who do not agree with the assertions in my footnotes.

A. P. R. WADLUND

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[1] The pound is a unit of force and not mass, despite the fact that in this country the relation between the kilogram and pound is legally fixed. It is just at this point that a student has his first real difficulty. The question naturally arises: If a certain "chunk" of metal which happens to be in France is taken as a unit of mass (the kilogram) why is it that another "chunk" of metal which happens to be in England is not a unit of mass but is the measure of a unit of force (the pound)?

[2] The writer understands an *absolute* system to be one that employs mass, length and time as fundamental units, and the *gravitational* system to be one that uses force, length and time. If this distinction is accepted, then the absolute units of force are the dyne and poundal; of mass, the gram and pound; whereas the gravitational units of force are the gram and pound; of mass, the slug or g-pound in the English system and an unnamed mass in the metric system found by dividing the weight of one gram by the numerical value of the acceleration due to gravity. There are some mechanics textbooks that use English units almost exclusively for numerical problems or ask for symbolic solutions when numerical values are not given. This is hardly an acceptable manner in which to avoid a difficulty.

The Bernoulli Equation

THE usual method of deriving the Bernoulli equation is to consider an element of mass in an incompressible fluid and, by applying the law of conservation of energy, to show that if its kinetic energy increases owing to an increase in its velocity, then its potential energy due to the pressure must decrease. Van Lear[1] has pointed out the fallacy of "pressure energy" in an incompressible fluid. In the present note, the Bernoulli equation is derived for a special case without reference to "pressure energy" or to energy at all. This rather obvious procedure is probably not new, although a rather extensive search of the literature has not revealed its use before.

Consider an incompressible fluid flowing in a pipe which, for simplicity, may be considered horizontal and smooth. Let the pipe have a constriction in the region A (Fig. 1). We may choose as an element of volume an infinitesimal cube $dxdydz$ so oriented in the fluid that the edge dx is along a stream line. If P is the pressure on the left-hand face of the cube, the force on this face will be $Pdydz$. The pressure at the right-hand face of the cube will be $P+(dP/dx)dx$, and the force on this face will be $[P+(dP/dx)dx]dydz$. The net force on the element is therefore

$$Pdydz-\{P+(dP/dx)dx\}dydz$$

or

$$-(dP/dx)dxdydz.$$

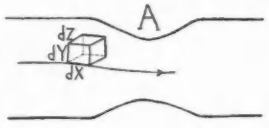

FIG. 1. Derivation of the Bernoulli equation.

The forces on the opposite faces $dxdz$ and $dxdy$ produce no acceleration along a stream line. Since $ma=F$, we may write

$$\rho dxdydz\cdot d^2x/dt^2=-(dP/dx)dxdydz$$

or

$$\rho d^2x/dt^2=-dP/dx,$$

where ρ is the density of the fluid. This is the Bernoulli equation in differential form.

The solution may be obtained by placing

$$d^2x/dt^2=dv/dt=(dv/dx)(dx/dt)=v\cdot dv/dx.$$

We now have

$$\rho v\cdot dv/dx=-dP/dx,$$

and this, on integration, gives

$$\tfrac{1}{2}\rho v^2+P=\text{constant},$$

which is the Bernoulli equation in the form usually given.

V. E. BOTTOM

Friends University,
Wichita, Kansas.

[1] Van Lear, Am. J. Phys. (Am. Phys. T.) 6, 336 (1938).

Blueprints and Shadowgraphs as First Experiments in Photography

THE chemical and optical theories necessary for controlled work in the photographic laboratory are too complicated to be understood until after some classwork has been done; hence some simplification is necessary in the first few laboratory periods. This is usually accomplished either by replacing the usual complex camera by one of the simple pinhole type, or by giving explicit and arbitrary directions for every step of the process of exposing and developing a negative. A way out of the dilemma which we have found successful is to ignore the camera entirely and concentrate on prints, without even the use of negatives.

The first experiment is on the production and use of blueprint paper. Good quality typewriter paper is painted with a solution of equal parts of potassium ferricyanide (20 g to 150 ml of water) and ferric ammonium citrate (30 g to 150 ml of water). This painting may be done in diffuse daylight, but the sheets should be dried in the dark. Two or three coats may be necessary but the paper need not be completely dried between coats. We have found it possible to prepare and use the paper the same afternoon. Leaves, cut-outs or small objects may be used for silhouettes; if old negatives are used they should have considerable contrast and rather bold patterns. Printing takes from 5 to 10 min in sunlight or with photofloods in a reflector; the washing in tap water should be complete in

30 min. The simplicity of the entire process is enlightening; the function of the light in providing the energy for a chemical change is obvious, and the process of development and fixation by the water bath is visible. For students who have no previous photographic experience it seems particularly worth while. A similar experiment with printing-out paper is, of course, possible.

The second experiment introduces them to ordinary developing paper and darkroom technic but not in the ordinary way. We have a very exciting time with "rayographs" or "shadowgraphs." These are made directly on the paper by a judicious juggling of small objects, light and shadows. The paper, 5×7 in., is laid on the darkroom table, emulsion side up and held flat by a piece of glass if it curls badly. With only the red light on, the arrangement is made of the small objects—prisms and evaporating dishes, thumb tacks and calipers, in fact, anything small. Then a white light is flashed for 5 to 10 sec. If the light source is directly over the paper, a silhouette effect is produced; if held to one side and slightly above, the shadows become the important part of the design, usually in unexpected ways. The paper is developed in the usual way. The results have far more snap and a more extreme range than anything a beginner can hope to produce from his own negatives, and set a high standard for future work. In addition, it is a very inexpensive way to learn what not to do in a darkroom!

NORA M. MOHLER

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Visual Demonstration of Vacuum Tube Characteristics

OSCILLOGRAPHIC demonstration of the behavior of two-element and three-element vacuum tubes may be conveniently carried out with the device described below. Power for operation is derived entirely from the 60-cycle/sec line.

The lower portion of the wiring diagram in Fig. 1 shows a conventional rectifier and filter arrangement, except that four toggle switches have been added, so that the components of the filter may be removed separately from the circuit and one plate of the full-wave rectifier tube may be disconnected. The wave form of the voltage drop across the bleeder resistance will vary accordingly, and may be observed on the oscillograph screen in the usual manner. This portion of the device is, of course, usable for other purposes as an ordinary rectifier-filter unit.

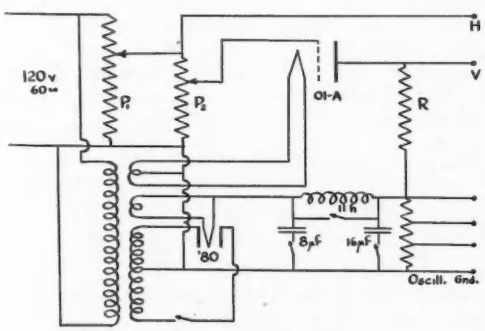

FIG. 1. Diagram of circuit.

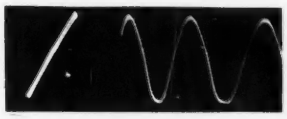

FIG. 2.

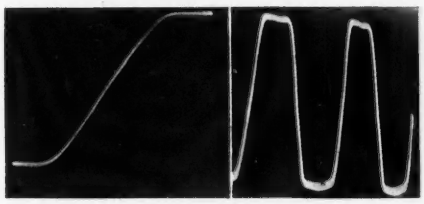

FIG. 3.

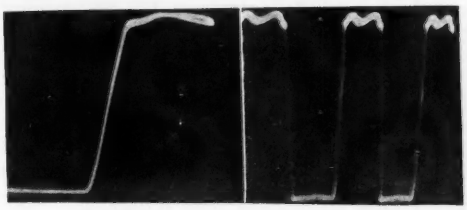

FIG. 4.

In the upper portion of the wiring diagram, a 25-w, 1000-ohm potentiometer P_1 applies a portion of the alternating line voltage to the horizontally deflecting (H) plates of the oscillograph and to a small 5000-ohm potentiometer P_2, which in turn applies a portion of the H voltage to the grid of an 01-A triode. The resulting voltage variation across the plate load resistor R is fed to the vertically deflecting (V) plates of the oscillograph.

In operation, the slider of P_2 is set at about its halfway position, and the slider of P_1 is slowly advanced from its lowest position. The pattern on the screen will be a straight line, of *slope* determined by the setting of P_2 and of *length* determined by the setting of P_1. At this point, if the oscillograph control system permits it, the linear sweep circuit is substituted for the H connection, and an undistorted sine curve appears (Fig. 2). Returning to the previous arrangement, the contact of P_1 is advanced far enough to show cutoff on the negative portion of the grid-voltage swing, and saturation on the positive portion. The sine wave can now be shown to have the corresponding distortion (Fig. 3). When P_1 has been advanced far enough so that, on the positive end of the grid swing, the grid "robs" the plate of some of its current, the characteristic curve will show a dip, and the sine curve will be distorted accordingly (Fig. 4).

All the parts of this unit are obtainable at small expense at radio supply houses.

EDWARD H. GREEN

Brooklyn College,
Brooklyn, New York.

Summer Courses, Symposiums and Meetings

A. A. P. T. AND A. A. A. S.

The American Association of Physics Teachers will participate in the summer meeting of the Pacific Division, American Association for the Advancement of Science, at Pasadena, California, June 17 and 18. There will be sessions for both contributed and invited papers. For further information, address Professor E. C. Watson, California Institute of Technology.

COLUMBIA UNIVERSITY

The following graduate courses will be offered in the summer session, July 7 to August 15: *Analytical mechanics*, R. von Nardroff; *Thermionics and photoelectricity*, G. N. Glasoe and C. G. Stone; *Elementary quantum mechanics*, A. Nordsieck.

CORNELL UNIVERSITY

In the summer session, July 7 to August 15, L. P. Smith and L. G. Parratt will offer a special course on *Theoretical and experimental electronics*, designed to meet the needs of students having varying degrees of preparation and experience in this field. The advanced laboratory will also be open for work in a wide variety of fields.

S. P. E. E. PHYSICS PROGRAM

The following sessions of especial interest to physicists who teach courses for engineering students are planned for the annual meeting of the Society for the Promotion of Engineering Education, Ann Arbor, Michigan, June 23 to 27.

June 23

The functions of physics courses in the engineering curriculums. Panel discussion. (1) *Electrical engineering*, A. S. LANGSDORF, *Washington University;* (2) *Chemical engineering*, R. C. ERNST, *University of Louisville;* (3) *Mining and metallurgical engineering*, E. A. HOLBROOK, *University of Pittsburgh;* (4) *Civil engineering*, L. E. GRINTER, *Illinois Institute of Technology;* (5) *Mechanical engineering*, H. B. DIRKS, *Michigan State College;* (6) *Physics*, E. P. SLACK, *Polytechnic Institute of Brooklyn.*

June 24

The industrial applications of the spectrograph. R. P. SAWYER, *University of Michigan.*

At a luncheon meeting on June 24, O. S. Duffendack, University of Michigan, will lead a discussion on what physics departments should undertake to accomplish in the limited time allotted to physics in the engineering curriculum, and on the question of duplications between the work offered in physics and in engineering. For additional information concerning the program, address Professor J. G. Potter, South Dakota State School of Mines, Rapid City.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

The ninth summer program on spectroscopy and its applications will be held during the six weeks from June 16 to July 25. A course on *Practical spectroscopy*, consisting of 18 two-hour lectures, will be given on three days a week in the late afternoon hours, so as not to interfere with the laboratory work. A course on *Applied spectroscopy* will involve four hours of laboratory work per day, five days a week. These courses will cover spectroscopic analysis of materials by study of their emission and absorption spectra, and the general application of the spectroscope and its auxiliary apparatus to problems of science and industry. The only prerequisite of the courses is sophomore work in physics in any accredited university.

The annual *Conference on spectroscopy and its applications* will be held on July 21, 22 and 23. It will repeat to a considerable degree the type of program presented at the conferences held during the past eight summers.

For additional information, address Professor G. R. Harrison.

OHIO STATE UNIVERSITY

A conference on molecular structure will be held in the first week of the summer quarter. A member of the University staff will review a topic and, after time for discussion, invited speakers will present papers on related research. An abbreviated program follows.

The electronic structure of molecules. L. H. THOMAS; G. HERZBERG, *University of Saskatchewan;* R. MULLIKEN, *University of Chicago.* June 25.

Nomenclature. A discussion. June 25.

Rotation-vibration spectra. H. H. NIELSEN; D. DENNISON, *University of Michigan;* G. HERZBERG, *University of Saskatchewan.* June 26.

Thermodynamic properties of molecules. H. L. JOHNSTON; E. B. WILSON, *Harvard University;* L. H. THOMAS, *Ohio State University.* June 27.

Large molecules. E. MACK; H. EYRING, *Princeton University.* June 28.

For further information, address Professor L. H. Thomas.

STANFORD UNIVERSITY

J. H. Van Vleck, of Harvard University, will give courses on *Introduction to the theory of electric and magnetic susceptibilities* and *Magnetism and very low temperatures.* F. Bloch will offer *Theory of collisions.*

STATE UNIVERSITY OF IOWA

The sixth Summer Colloquium for College Physicists, June 12, 13 and 14, will include the following addresses and round table discussions:

Recent research and the teacher. W. S. HUXFORD, *Northwestern University.*

Laboratory demonstrations. P. L. COPELAND, *Illinois Institute of Technology;* H. L. CUNNINGHAM, *Boone Junior College;* R. R. HANCOX, *Woodrow Wilson Junior College;* J. HARTY, *Cape Girardeau State Teachers College;* R. E. HARRIS, *Lake Forest College;* W. J. HOOPER, *The Principia;* J. C. JENSEN, *Nebraska Wesleyan University;* A. F. JOHNSON, *Rockford College;* L. A. ROHRET, *St. Ambrose College;* V. F. SWAIM, *Bradley Polytechnic Institute.*

The flight of the projectile. R. H. KENT, *United States Army.*

The high school situation in physical science and its relation to public welfare in a machine age. K. LARK-HOROVITZ, *Purdue University.*

What are the inherent weaknesses in pure textbook study? R. M. SUTTON, *Haverford College;* F. W. COOKE, *Illinois College;* W. P. GILBERT, *Lawrence College;* J. N. SAYLER, *Northwest Missouri State Teachers College;* W. M. ROBERDS, *University of Arkansas.*

What classroom teaching devices are peculiarly effective? R. M. SUTTON, *Haverford College;* F. E. HOECKER, *University of Kansas City;* M. A. COUNTRYMAN, *Illinois Institute of Technology;* J. W. HORNBECK, *Kalamazoo College;* P. E. FOSSUM, *St. Olaf College.*

Meteorology in our defense. H. E. BYERS, *Institute of Meteorology, University of Chicago.*

University lecture. H. SHAPLEY, *Harvard Observatory.*

Case reports on accomplishment in laboratory instruction. J. C. STEARNS, *University of Denver;* R. D. SPANGLER, *La Crosse State Teachers College;* L. B. HAM, *University of Arkansas;* J. L. HUNDLEY, *University of North Dakota;* R. H. MORTIMORE, *Granland College.*

The most satisfactory type of requirement for the laboratory report. J. C. STEARNS, *University of Denver;* C. N. WALL, *North Central College;* R. MORROW, *Iowa Wesleyan College;* H. E. HAMMOND, *University of Missouri;* L. T. EARLS, *Iowa State College.*

Round table discussions are also planned for several of the luncheon and dinner meetings. Notice of attendance at the Colloquium should be sent promptly to Professor G. W. Stewart.

UNIVERSITY OF MICHIGAN

A symposium in theoretical physics will be held again this summer from June 30 to August 22, with emphasis on field theory, nuclear problems and the theory of solids. In addition to the special lecture courses listed below, there will be colloquiums twice a week where current developments are presented and discussed.

Review of recent field theories. W. PAULI, *Institute for Advanced Study.* June 30–August 8.

Special topics in the theory of solids. F. SEITZ, *University of Pennsylvania.* June 30–July 26.

The problem of nuclear forces. J. SCHWINGER, *University of California.* July 21–August 15.

The yield of nuclear reactions. V. F. WEISSKOPF, *University of Rochester.* July 7–July 17.

An unusually complete program of courses for graduate credit will also be offered.

UNIVERSITY OF PITTSBURGH

Continuing the policy of previous years, the department has arranged a special session on "Physics of Metals," from June 16 to July 25, in which physicists and metallurgists will cooperate in lectures and discussions on recent progress in the physics of metals and possible applications in the field of metallurgy. In addition to weekly colloquiums on topics of especial interest, the following formal courses will be offered:

Electronic structure of metals. C. S. SMITH, JR.
Recent advances in metals. Special lecturers.
Light, color and illumination. W. N. ST. PETER.
Spectroscopic analysis of metals. M. E. WARGA.
X-ray analysis of metals. S. S. SIDHU.

A regular program of summer courses will also be available from July 1 to August 22.

UNIVERSITY OF CHICAGO

In addition to the usual schedule of graduate courses by members of the regular staff, the following special courses in physics and chemistry will be offered:

Properties and reactions of nuclei. E. TELLER, *George Washington University,* June 24–July 25; J. A. WHEELER, *Princeton University,* July 28–August 28.

Diffraction methods of determining the structure of molecules and crystals. L. PAULING, *California Institute of Technology,* June 24–July 25.

The chemical bond and the structure of molecules. L. PAULING. June 24–July 25.

Other special features will be three weekly seminars—on *Cosmic rays*, *Nuclear structure* and *Spectroscopy and molecular structure*—and a course on the theory and technic of radio circuits and tubes.

Science education. Two courses designed for those interested in teaching integrated courses in the physical sciences at the senior-high-school and junior-college levels will be offered from June 23 to August 28. A conference for teachers will be held June 30 to July 2.

THE defect of the present content and outlook of humanistic education as a preparation for leadership in a democratic society may all be summed up in the single statement that knowledge is encouraged as a means to more knowledge instead of being a means to action. The only part of the educational curriculum which makes demands on *ability to do* in contradistinction to *facility of expression* is experimental science. So individuals with conspicuous executive capacity, that is, ability *to do* as opposed to ability *to dispute*, are attracted to the natural sciences and technology. Since neither natural sciences nor any form of manual craftsmanship are obligatory in humanistic education, nothing is done to develop general competence in those who elect a course of social studies because they lack constructive aptitude. The machinery of educational selection therefore tends to recruit the nation's statesmen from those who can talk glibly, write elegantly or argue forcibly without a capacity to act competently. When the need for action is urgent they can only continue to talk glibly, write elegantly and argue forcibly. If democracy can produce only leaders who can talk, it is doomed, and we can only hope to preserve it by a policy of educational selection which favors competence more than fluency.—LANCELOT HOGBEN, *Retreat from Reason.*

Instructorship in southeastern engineering college. Probable salary, $1650. Opportunity for a man with a Master's degree to secure several years' teaching experience before completing his graduate work.

Annual Meeting of the Southeastern Section of the American Physical Society

THE seventh annual meeting of the Southeastern Section of the American Physical Society was held at Vanderbilt University, Nashville, Tennessee, on April 4–5, 1941. Approximately 160 members and guests attended the meeting. Local arrangements were made by a committee headed by F. G. Slack.

The program consisted of 20 contributed papers and a symposium of invited papers on molecular structure as follows:

Use of Isotopes in Molecular Spectra. E. TELLER, *George Washington University.*

Absorption Spectra of Substituted Benzenes. HERTHA D. E. SPONER, *Duke University.*

Interaction Theory and Anomalies in the Infra-Red Spectra of Polyatomic Molecules. H. H. NIELSEN, *Ohio State University.*

The Structure Determination of Molecules and Groups in Crystals by Means of X-Ray Diffraction. ROSE C. L. MOONEY, *Sophie Newcomb College.*

Abstracts of contributed papers relating to instruction appear below. Abstracts of other contributed papers will appear in *The Physical Review*, June 15 (1941).

At the business meeting the election of the following officers for the year 1941–1942 was announced: *Chairman*, Fred Allison; *Vice Chairman*, W. S. Nelms; *Secretary*, E. S. Barr; *Treasurer*, C. B. Crawley; *Members of the Executive Committee*, F. G. Slack (4 years), R. S. Williamson (1 year). The 1942 annual meeting will be held at the University of Mississippi.

E. S. BARR, *Secretary*

ABSTRACTS OF CONTRIBUTED PAPERS

1. Lucite Accessories for the Stevens Optical Disk. C. C. SARTAIN, *University of Alabama.*—An optical disk 5 ft in diameter has been constructed. Prisms and cylindrical lenses made of Lucite are placed in a beam of light up to 10 in. wide for demonstrating the usual principles of optics. The method used in cutting and polishing the optical surfaces is so simple that the work was largely done by a second-year student of physics.

2. A Laboratory Experiment on Illumination. S. C. GLADDEN, *University of Mississippi.*—The complete article will appear in the August issue.

3. Display Project. I. V. RAGSDALE, *University of Tennessee.*—The display of equipment and experiments is educational and develops interest in the subject of physics. Experience has shown that equipment of a historical nature or experiments involving motion receive the most comment and interest. An important factor in the project is an electric motor with reduction to 2 sec/rev; this repeats the cycle often enough to hold interest and allows sufficient time in which to show the principle involved. Among the easily controlled experiments are: Cartesian diver, Bernoulli effect on vibration of a bar supported by springs, effect of a.c. and d.c. on the lighting of a neon lamp, color by rotation of Polaroids, electric eye control. Some possible stationary experiments are: floating ball under an air jet, lift of an electromagnet, real images, Hero's fountain, piping of light with Lucite.

4. Covering the Textbook. A. A. BLESS, *University of Florida.*—Most teachers seem to feel obligated to cover the whole of the textbook they use in the elementary course. This prevents the teacher from spending a little more time on portions of the subject that he could make much more vivid and interesting because of his peculiar training and experience. It would seem wiser to omit, if need be, whole sections of the subject matter usually found in an elementary book if the time is profitably spent on some other part of physics.

5. A Temperature Concept for Elementary Students. W. NOLL, *Berea College.*—The temperature concept is adequately discussed by Wensel[1] and by Worthing.[2] Their treatment may be developed further in order to make the concept simpler for beginners. The development of the concept begins with the sensation of hotness, a universally recognized experience. By the use of a series of appropriately chosen experiments involving various sensations, universal agreement can be secured that certain bodies are hot and others are cold. Certain readily measured physical properties vary with the degree of hotness of the body. Thus mercury increases in volume as it is taken from a cold to a hot body. Since there is a correspondence between volume increases and the increase of hotness, as Fahrenheit observed, it may be assumed that this volume change is a measure of the change of the property of the body which gives the sensation of hotness. If the volume is measured upon an arbitrarily chosen scale, the reading on this scale may be defined as temperature. From theoretical and experimental considerations it may be concluded that the pressure of a gas at constant volume offers the most convenient way of defining temperature. Temperature is a quantitative description of the property of a body which gives the sensations. It is the reading of a thermometer involving numerical values.

[1] H. T. Wensel, J. App. Phys. 12, 373 (1940).
[2] A. G. Worthing, Am. J. Phys. 8, 28 (1940).

6. Appraisal and Criticism of Survey Courses. E. H. DIXON, *University of Georgia.*—This appraisal and criticism is based on experience with survey courses given in the University System of Georgia for several years. These courses afford the student an opportunity to become acquainted with a wide field of knowledge and to become familiar with various methods of approaching problems. However, the tendencies are to employ young and inexperienced teachers, to allow the courses to degenerate into memory courses, to duplicate high school courses in both content and teaching methods, and to discourage serious minded students because of the pressure to lower standards of teaching on account of the wide range of pre-college preparation.

RECENT PUBLICATIONS AND TEACHING AIDS

Intermediate Textbooks

Temperature Measurement. Robert L. Weber, Pennsylvania State College. 188 p., 156 fig., 34 tables, 22×27 cm. *Robert L. Weber, Pennsylvania State College*, $2.50, lithoprinted, paper cover. This book represents the substance of a one-semester course consisting of one recitation and one three-hour laboratory period each week, which the Department of Physics of the Pennsylvania State College has been giving for several years to large classes of junior students of the physical sciences, engineering, metallurgy and ceramics. One year of general physics is the prerequisite. A compact, up-to-date treatment of the theoretical and practical basis of temperature measurements is given in 15 chapters covering the first 117 pages of the book; accompanying these chapters are lists of problems, diagrams and many specific references to periodicals and books. The next 34 pages contain the directions for 22 experiments on various methods of temperature measurements and on processes involving temperature measurement and control. In an appendix, as well as in the text proper, there are many tables of useful and strictly modern data.

A Textbook on Light. A. W. Barton, Headmaster of King Edward VII School, Sheffield. 436 p., 279 fig. and plates, 14×22 cm. *Longmans*, $3. The method of presentation employed in this skillfully written textbook is referred to by the author as "dynamic"; that is,

> ". . . it is not a logical method, nor is it historical in the sense that there is any reference to the life history of pioneer workers. But it is historical in . . . that the discovery of facts and the development of ideas are presented as they occurred historically. When the set of facts . . . known at a certain date have been discussed . . . , the theories which were put forward to correlate them are expounded solely in the light of those facts. There is no dogmatic suppression of one theory because the teacher, with his wider knowledge of facts, is aware that later evidence will rule it out. The reader is therefore treated as if he were at the frontiers of knowledge; he is made to exercise his critical faculty in deciding which of the two theories is the more satisfactory; his interest is aroused by the uncertainty of the situation and the conflict of ideas, and he sees how new lines of investigation are suggested by the deductions made from the theories. So he learns that scientific knowledge grows by a judicious interplay between experiment and theory. . . ."

The first half of the book is devoted to geometrical optics, the whole structure of which is built up as a logical deduction from the laws of reflection and refraction. Practical applications are kept continually in view, and more than ordinary emphasis is given to such subjects as image defects and photometry. The last half of the book, on physical optics, is especially well done, and it is here that the author is at his best in the use of the "dynamic" method of presentation. The convention of signs used throughout the book is the first of the two recommended by a committee of the Physical Society of London [see Am. J. Phys. (Am. Phys. T.) **3**, 140 (1935)].

Advanced Books

The Stereographic Projection. F. W. Sohon, Director, Seismological Observatory, Georgetown University. 219 p., 54 fig., 22 tables, 14×22 cm. *Chemical Publishing Co.*, $4. The subject of stereographic projection is here developed from its foundations, and in such a manner as to make evident its usefulness in solving certain problems or as a practical tool, not only in cartography, but in seismology, astronomy, hydrodynamics, crystallography, the theory of the complex variable and differential geometry. Alternative proofs by vector methods are supplied in a few cases.

Cambridge Physical Tracts. Paper covers, 14×22 cm. *Cambridge University Press* and *Macmillan*.

Electron-Inertia Effects. F. B. Llewellyn, Bell Telephone Laboratories. 114 p., 13 fig. $1.75. The modern theory of electron-inertia effects and those applications that are in most general use today are reviewed under the following chapter headings: Significance of the effects; Fundamental equations; Direct-current relations; First-order solution; First-order relations in diodes; First-order relations in negative-grid triodes; Second-order effects; Other electron-inertia effects.

Surface Tension and the Spreading of Liquids. R. S. Burdon, University of Adelaide. 95 p., 22 fig. and plates. $1.75. Emphasis is placed on those aspects of the subject that are not treated in textbooks, or concerning which uncertainty exists or progress is being made. The main topics discussed are the nature of surface forces, measurement of surface tension, the surface of liquid metals, general conditions for spreading, spreading on the surfaces of mercury and of water, and liquids on solid surfaces. The author reminds us that "after a century of work we do not know the surface tension of mercury nor even exactly why it is difficult to determine this quantity, and that few have any ideas as to what methods of measuring surface tension give reliable results."

Cosmic Rays and Mesotrons. H. J. J. Braddick, Birkbeck College (London). 72 p., 16 fig. $1.50. About half of this tract is devoted to experimental methods and facts concerning the variation of cosmic-ray intensity with time and latitude, the absorption of the rays in matter, and the characteristics of showers and bursts. In the remaining pages, the facts are explained in terms of the properties predicted by quantum theory for moving charged particles.

Some Problems in Adsorption. J. K. Roberts, University of Cambridge. 130 p., 33 fig., 7 tables. $2. The work described in this tract was carried out to obtain data that should form part of the basis of a physical theory of the

interaction between known gas atoms or molecules and known solids, and to develop, as far as possible, a mechanical picture of the events occurring at the surface. After describing the experimental methods, the author discusses the theory of heat of adsorption with interaction between adsorbed particles, the process of the formation of adsorbed films, evaporation processes and the production of atomic hydrogen, other types of adsorption, some effects of dipole interactions, and some properties of oxygen films on tungsten.

Geophysics and Meteorology

Physics of the Air. W. J. Humphreys. Ed. 3. 690 p., 226 fig., many tables, 15×23 cm. *McGraw-Hill*, $6. Much information of recent date—especially on the topics of humidity, evaporation, vertical distribution of temperature, lightning and the halo—has been added to the present edition of this well-known book on the mechanics and thermodynamics of the atmosphere, atmospheric electricity, meteorological acoustics, atmospheric optics and factors of climatic control. The general plan and the scope, however, are the same as those of the second edition (1928).

Meteorology for Aviators. R. C. Sutcliffe. 317 p., 110 fig., 17 tables, 14×22 cm. *Chemical Publishing Co.*, $4. Prepared under the auspices of the Meteorological Committee, British Air Ministry, this textbook is designed particularly for the intelligent pilot who has neither the time nor the basic training to study the whole literature of meteorology. Although relatively elementary, the treatment is logical and it covers all phases of meteorology of value in aviation.

Meteorology. Donald S. Piston, Physicist, The Twining Laboratories. Ed. 2. 243 p., 113 fig. and maps, 9 tables, 14×21 cm. *Blakiston*, $3.00. Although designated for a one-semester college course without prerequisites, this textbook is not a mere collection of apparently unrelated meteorological facts. Instead, it provides brief, elementary explanations of the underlying physical processes and principles, and then describes the phenomena in terms of them. Presenting meteorology as a branch of physics, it shows that a correct understanding of weather phenomena can be had only by studying certain principles of physics and learning how to apply them to atmospheric phenomena. In the present, revised edition of the book an elementary discussion of air mass methods and their applications has been added. Certain of the climatic charts have been replotted to advantage by employing two modifications of Cahill's octahedral projection, instead of the Mercator projection previously used. A set of 75 problems and questions adds materially to the value of the book.

Geophysical Exploration. C. A. Heiland, Professor of Geophysics, Colorado School of Mines. 1026 p., many figures, 86 tables, 15×23 cm. *Prentice-Hall*, $8 (school price), $10 (trade price). The fundamentals of geophysical methods, and their common features and differences, are emphasized in this survey of the entire field of geophysical exploration. An introductory section of 64 pages is devoted to an elementary description of working principles and methods, and their applications in oil exploration, mining, geology and engineering; this section is designed for the reader who is not directly concerned with field or laboratory operation. The remainder of the book is intended for the technical student of geophysics. Written from the engineering point of view, it deals with the geophysical theory, field technic, laboratory procedure and geologic interpretations involved in gravitational, magnetic, seismic, electrical and other geophysical methods. Emphasis is placed on material that will give the geophysicist understanding of the geologist's reasoning in selecting and interpreting geophysical methods and data, and that will acquaint the geologist with the mathematical and physical approach to instrument and interpretation problems.

Science Teaching

The Teaching of Science in Elementary and Secondary Schools. Victor H. Noll, Associate Professor of Education, Michigan State College. 248 p., 2 plates, 14×22 cm. *Longmans*, $2. Designed for the use of teachers and as a textbook for a course in teaching methods and materials, this book draws upon unpublished theses and the published literature to provide a broad survey of the major constructive suggestions yielded by experiments in science teaching at elementary and secondary levels.

Prints

The Alchemist. 15×19 cm, enamel paper. *Fisher Scientific Co.* (711 Forbes St., Pittsburgh), gratis to colleges. An engraver's print of an oil painting signed by Charles Meers Webb and dated 1858.

Periodicals

Taylor-Rochester. *Taylor Instrument Co.* (Rochester, N. Y.), gratis to colleges and schools.

Pamphlets

Tables of Constants for Pyrometers. 11 p. *Foster Instrument Co.* (Letchworth, Herts., England), gratis. Contains much useful data.

Development and Manufacture of Optical Glass in America. M. H. Eisenhart and E. W. Melson. 12 p. *Bausch and Lomb Optical Co.* (Rochester, N. Y.), gratis.

Motion Pictures

Youth Takes to Wings. 16 or 35 mm, silent, 52 min. *Bray Pictures Corp.* (729 Seventh Ave., New York), rental. Simple ideas of aerodynamics; slow-motion pictures of bird flight; demonstrations of air flow, force, mass, density, thermals; etc.

Principles of Flight. 16 or 35 mm, silent, 15 min. *Eastman Teaching Films* (Rochester), sale only. Elementary principles of lift and flight; effects of air currents and wing angles; standard controls.

DIGEST OF PERIODICAL LITERATURE

Apparatus and Demonstrations

A space model of the Carnot Cycle. E. W. Kanning and R. J. Hartman; *J. Chem. Ed.* **18**, 180–181 (1941). The model (Fig. 1) is made of plaster of Paris set on a wooden base. One mole of an ideal gas is represented: *A*, 2 A., 546°K; *AB*, isothermal expansion; *B*, 1 A., 44.8 l, 546°K;

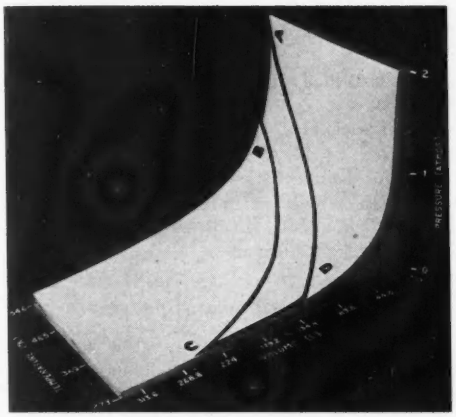

Fig. 1. Photograph of the model.

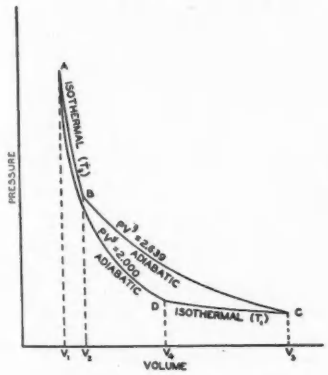

Fig. 2. The Carnot cycle in the *PV* plane.

BC, adiabatic expansion, $PV^{1.4}=2.639$; *C*, 273°K; *CD*, isothermal compression; *DA*, adiabatic compression, $PV^{1.4}=2.000$. Figure 2 is an accurate projection on the *PV* plane of the surface *ABCD* outlined on the space model.—D.R.

Simple method of constructing glass cells. L. W. Mullinger; *Sch. Sci. Rev.* **22**, 324 (1941). A length of glass rod, of diameter somewhat greater than the thickness of the cell required, is bent into a **U** and opposite faces of the **U** are ground with a paste of carborundum powder and water on a flat iron plate. The resulting flats on the glass rod should be 3 or 4 mm wide. Glass plates (photographic plates cleaned of emulsion are suitable) are cemented to the rod to form the cell. The cement may be Canada balsam, optical cement or bichromated gelatine; it must, of course, be insoluble in the liquid which the cell is to contain and must remain rigid at the working temperature of the cell. Such a cell is useful in the projection lantern and for other purposes.—J.D.E.

Apparatus for proof of the centrifugal force formula, mv^2/r. W. H. Dowland, N. Herbert; *Sch. Sci. Rev.* **22**, 330 (1941). A disk of metal is cut to fit a phonograph turntable. A piece of square brass rod is fastened along a radius of the disk, a few millimeters above it, by brass angles soldered to the rod and the disk. The rod carries a slider made of a short length of square brass tube, which can be clamped to the rod by a set screw. One end of a piece of narrow clock spring is clamped in a slotted post on the slider; the other end carries a hollow, vertical, brass cylinder, in which a steel phonograph needle is free to slide. The point of the needle rests on a piece of smoked glass fastened to the disk. When the turntable rotates, the brass cylinder moves outward, approximately along a radius of the disk, until the necessary centripetal force is provided by the spring, and as it moves, the needle makes a trace on the smoked glass. The force required to move the needle outward over the same trace is measured, with the turntable at rest, by means of a cord attached to a spring balance. From the known rate of rotation of the turntable, the distance from the center of rotation and the mass of the cylinder, the expression mv^2/r can be tested. All three variables can be changed, the last by the addition of slotted hollow brass cylinders to that carried by the end of the spring. The mass of the spring is neglected.—J.D.E.

Freely rotating suspension made from magnet and ball bearings. W. H. Dowland; *Sch. Sci. Rev.* **22**, 331 (1941). A torsionless and almost frictionless suspension can be made by attaching a steel ball above the center of gravity of the apparatus to be suspended and supporting the ball from an electromagnet or a permanent magnet. A modified form of Ampère's apparatus, for showing the revolution of a current-carrying conductor in a magnetic field, can be made in this way. Two cylindrical cobaltchrom magnets are mounted vertically, one above the other. The upper one supports three small steel balls, in a vertical chain, to the lowest of which is soldered one end of a piece of copper wire. The other end of the wire is soldered to a larger steel ball, which rests against the lower magnet. A direct current is sent through the wire by way of the two magnets, and the wire revolves in the field of the lower magnet. The

magnets and balls must be clean. A coin may be hung in this way from the lowest of three balls, to which it is waxed so as to hang in a horizontal plane. It is set into rotation by blowing against its milled edge through a glass tube. Such a coin continued spinning for 17 min after it was set into rotation.—J.D.E.

Women in the Sciences

Women in *American Men of Science*. A. Wupperman; *J. Chem. Ed.* **18**, 120–121 (1941). Of the 28,000 scientists listed in *American Men of Science* (ed. 6, 1938), 800 are women. Of these women, 382 were in some branch of biology, 227 in chemistry, 40 in physics, 18 in geology, 16 in astronomy, 10 in home economics, 1 in optics and 1 in physical metallurgy. Of the 42 in physics, optics and physical metallurgy, 29 had the doctorate and 11, the master's degree; 31 were teaching, 7 were in research or technical work and 4 were in the government service. —D.R.

Check List of Periodical Literature

A physicist's view of ethics. G. A. Fink; *Sci. Mo.* **52**, 146–155 (1941).

Religio scientiae. C. D. Leake; *Sci. Mo.* **52**, 166–173 (1941). Attempts to show that J. S. O'Conor's argument in "A scientific approach to religion" [*Sci. Mo.* **51**, 368 (1940)] is scientifically questionable. A reply by O'Conor appears in the same issue, p. 173.

Scientists look at astrology. B. J. Bok, M. W. Mayall; *Sci. Mo.* **52**, 233–244 (1941). Summary of a scientific investigation of astrology.

Science progress through publicity. A. H. Clark; *Sci. Mo.* **52**, 257–260 (1941). We should take the public completely into our confidence. Science news writers should be given all the material they can use.

A preface to solar research. D. H. Menzel; *Sci. Mo.* **52**, 320–336 (1941). Unsolved problems of solar astrophysics, and possible ways of attacking them. Good photographs.

The electron microscope. T. A. Smith; *Sci. Mo.* **52**, 337–341 (1941). Includes reproductions of several interesting micrographs.

Physics in 1940. T. H. Osgood; *J. App. Phys.* **12**, 84–99 (1941). A survey.

Let's get acquainted with patent law. W. F. O'Connor, Jr.; *J. Chem. Ed.* **18**, 62–64 (1941). An outline and bibliography for the use of science students.

Preparation of Weston standard cells. W. C. Vosburgh, P. F. Derr; *J. Chem. Ed.* **18**, 87–89 (1941). A set of directions designed for student use.

Arthur Erich Haas, 1884–1941

A DISTINGUISHED career in the development and teaching of modern physics was terminated with the death of Professor Arthur E. Haas, in Chicago, on February 20, 1941. His death ended a long illness with which he was stricken in Chicago last November, following the presentation of a paper at a meeting of the American Physical Society.

Professor Haas' early education was received in Brno, Moravia, where he was born on April 30, 1884. He studied at Göttingen and later at Vienna, where he received his doctorate in physics in 1906. He remained at Vienna as postgraduate and privat docent until 1913 when he was appointed Professor of Theoretical Physics at Leipzig. In 1923 he returned to Vienna as Professor of Theoretical Physics. During the years of his Vienna professorate (1923–1936), he traveled abroad as visiting lecturer, once in England and twice in America. In 1935 he came to Bowdoin College as Tallmann Visiting Professor. The following year he joined the faculty of the University of Notre Dame, where he remained until his death. Professor Haas was well acquainted with a large number of physicists in America, as a result of his extensive lecture trips that included some 86 universities and colleges.

This genial scientist was conspicuous both in research and in teaching. Among his notable achievements in the field of research was his development, in 1910, of the formula for Rydberg's constant which contained only elementary constants. This formula differs only by a numerical factor from the famous formula developed three years later by Niels Bohr; this difference was due to the fact that Haas used the Thomson atomic model then in vogue, whereas Bohr used the Rutherford model. In 1920, Professor Haas developed the theory of the isotopic effect in band spectra independently of Loomis and Kratzer, who were also developing the same theory. In later years, his interest in atomic and cosmic constants led to the discovery of relations that were used subsequently by Eddington, Jordan and others.

But his splendid energies were not confined to research. As a teacher, Professor Haas introduced modern theoretical concepts to many physicists both here and abroad. He was the author of the first modern textbook on theoretical physics. As an authority in the history of physics, he published a work on the historical development of the fundamental concepts of mechanics. In a series of articles, he wrote on the history of physics among the ancient Greeks. He was editor-in-chief and contributor to the *Commentary on the Scientific Writings of J. Willard Gibbs* (Yale University Press, 1936). His pedagogic works have been translated into ten languages. At the time of his death he was working on a new English edition of his *Introduction to Theoretical Physics*.

His profound awareness of the importance of science in modern culture led him to assist in the important work of making its contributions available to the laity. He was a charming and witty popular lecturer with a genuine flair for representing the essentials of his highly technical science to the uninitiated. On the campus at Notre Dame those endearing personal traits of loyalty, sincerity and kindliness made for him a host of devoted friends and admirers. His earnest and constant devotion to science inspired his students and colleagues alike. His was indeed a richly fruitful career.

Eugene Guth